[Reply to Comment by J. Egger, final revision, J. Atmos. Sci. **53**, 2105–7 (1996)]

Reply

P. H. Haynes,* M. E. McIntyre*,
T. G. Shepherd ‡

*Centre for Atmospheric Science@ at the
Department of Applied Mathematics and Theoretical Physics
University of Cambridge.

‡Department of Physics, University of Toronto.

The "downward control principle", as we called it, does not apply to everything in the atmosphere. It applies only to particular aspects of a particular time-dependent thought-experiment. We, and others, have found this thought-experiment useful in trying to understand the extratropical branches of chemically important global-scale stratospheric circulations, and their causally correct representation in general circulation models — including consideration of sensitivities to gravity-wave parameterization and to artificial upper boundary conditions (e.g., Garcia and Boville 1994, McIntyre 1989, 1995, Mote et al. 1995, Rosenlof and Holton 1993, Rosenlof 1995, Yulaeva et al. 1994).

The real atmosphere confronts us with a complicated problem, with its nonlinear, multi-scale, chaotically-evolving fluid dynamics intimately coupled to radiation and chemistry. The problem involves a whole variety of nonlocal effects, both radiative and fluid-dynamical, acting upwards, downwards and sideways (e.g., Holton et al. 1995, and references therein). Our approach was therefore to dissect the problem — to try to isolate different aspects, to discern any useful simplifying features, and to recognize what causes what. In particular, we tried to distinguish carefully between one-way causal links or "controls", on the one hand, and purely diagnostic links or two-way cross-connections on the other.[1]

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* *Corresponding author address:* Dr. Peter Haynes, Dept. of Applied Mathematics and Theoretical Physics, University of Cambridge, Silver Street, Cambridge CB3 9EW, United Kingdom.

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[1] It should be obvious that such distinctions are important for understanding any physical system, whenever they can be made. To ignore them can lead to mistakes like "thinking that the weather-vane determines the direction from which the wind shall blow, or that the thermometer keeps the room hot" (Jeans 1934). We are using the word "control" in the sense of saying that, on the contrary, to good approximation, the wind controls the weather-vane and the room temperature controls the thermometer reading.

We also tried to exploit the fact that some aspects of the global circulation problem are relatively well understood — notably, radiative cooling and boundary-layer friction, to the extent that both tend to be robustly *relaxational* in character — whereas others are less well understood and less well quantified. Foremost among the latter are the crucially important non-frictional, eddy-induced zonal forces associated with momentum transport by waves. The generally *non-relaxational* character of such forces is widely recognized, for instance through their role in phenomena like the quasi-biennial oscillation, and in other cases of what used to be called "negative viscosity". We therefore felt it useful to consider a thought-experiment in which such eddy-induced, or wave-induced, forces are sharply distinguished from boundary-layer friction, and treated entirely separately.

In that thought-experiment, we imagined applying a given zonally-directed, zonally-symmetric force $\overline{\mathcal{F}}$ to the extratropical stratosphere of a zonally-symmetric model atmosphere, and noted the response, especially the meridional circulation in view of its acknowledged chemical importance. That is, in order to isolate one aspect of the problem we deliberately replaced the real wave-induced force acting on the real extratropical stratosphere by the prescribed zonal force $\overline{\mathcal{F}}$ acting on a simplified model stratosphere. By contrast, boundary-layer friction, if any, was not prescribed but was treated relaxationally, along with radiative cooling, as part of the response.

Professor Egger's Comment (Egger 1995, hereafter "C") on our paper (hereafter "HMMSS") insists on lumping boundary-layer frictional forces together with stratospheric wave-induced forces. This obscures the physically real, and physically important, distinction between them, and leads to conceptual difficulties such as those aired in C and also in our section 2, item 2, p. 655.

C also suggests that HMMSS' thought-experiment has some kind of difficulty with its overall angular momentum budget. But there is no such difficulty with the thought-experiment as we conceived it. A sufficient illustration is the idealized extratropical situation sketched in Fig. 1a. This is a slight variant of the original thought-experiment, making the wave part explicit within a closed system, an idealized Earth-plus-atmosphere system that conserves its total angular momentum.

Specifically, we imagine that Rossby waves are generated at the Earth's surface by idealized, frictionless, smoothly-undulating planetary-scale orography at high latitudes, and that the waves propagate upward and equatorward and dissipate in the midlatitude stratosphere, giving rise to a westward force $\overline{\mathcal{F}}$ hence torque in the shaded region of Fig. 1a. The shaded region is imagined to be entirely within the extratropics, where Coriolis effects are strong. If the wave field becomes steady then there is an equal and opposite, eastward torque on the high-latitude orography.[2] The westward torque aloft, in the shaded region,

[2] This is a standard result from wave–mean interaction theory. It depends on the fact that for simplicity's sake the idealized problem neglects wave dissipation, including wave breaking, except in the shaded region. Hence — with steady, conservative, non-breaking waves elsewhere — there are no other mean torques on the idealized atmosphere. (In specialist language, we are invoking the Charney–Drazin nonacceleration theorem outside

induces the time-dependent zonal mean response described in sections 3*e* and 5 of HMMSS. After a sufficient time, all of the induced meridional circulation extends downward from the shaded region, closing off in a frictional boundary layer. The entire system, Earth plus atmosphere, approaches a steady state; and in that state the frictional force has adjusted itself — through small changes in near-surface zonal wind speeds — in such a way as to exert a westward torque on the Earth, equal and opposite to the eastward wave-induced torque on the orography.

Fig. 1b isolates the zonally symmetric part of the problem, the subject of detailed analysis and numerical experiments presented in HMMSS including the adjustment of the frictional boundary layer (HMMSS pp. 662a, 667). Fig. 1b is exactly the same as Fig. 1a aside from omitting the wave part of the problem. Fig. 1b does not, of course, represent a closed, angular-momentum-conserving system. But that is as it should be. The openness of the system, or rather, subsystem, is a natural consequence of having isolated this part of the complete problem.

What we called the "downward control of extratropical diabatic circulations by... mean zonal forces" was a way of saying that, in the time-dependent thought-experiment we considered, the subsystem tends toward the state implied by the "downward-control integral", Eq. (2) of C, and sketched in Fig. 1b. In particular, one does not get an "upward controlled" situation of the kind implied by Eq. (3) of C, and sketched in Fig. 1c.

One can rehearse more elaborate versions of Fig. 1a, for instance

(*a*) by allowing the waves to dissipate in a more extensive region, as they may well do in reality,

(*b*) by allowing the orography and the frictional boundary layer to overlap, as they certainly do in reality,

(*c*) by allowing for the feedback of zonal-wind changes on the wave field,

(*d*) by allowing for all the various non-orographic and nonlinear wave sources including tropospheric storm-track eddy fluxes,

and so on, conserving angular momentum in each case and leading all the way to the cutting edge of elaborate general-circulation modelling. But the principles remain entirely the same and, as with Fig. 1a, there is never any difficulty with angular momentum conservation itself.

To summarize the essentials, then, HMMSS tried to say in words what Fig. 1a tries to say pictorially (HMMSS p. 652): "The idea of 'control' by $\overline{\mathcal{F}}$ is not meant to suggest that other causal links are considered unimportant, such as the feedback of the mean state on

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the shaded region or, rather, its finite-amplitude generalizations related to the Kelvin–Bjerknes circulation theorem and the potential-vorticity invertibility principle. The theory goes back to Lord Rayleigh; see McIntyre and Norton (1994) and references therein.)

the generation, upward propagation, and dissipation of the Rossby and gravity waves that are believed to be crucial, in turn, to determining $\overline{\mathcal{F}}$. However, one reason why thought-experiments involving manipulation of $\overline{\mathcal{F}}$ seem useful, in the present state of knowledge, is that the other causal links just mentioned are relatively ill-understood. Therefore, they need separate consideration in any attempt to understand the circulation."

By contrast, the feedback on boundary layer friction is, as already emphasized, relatively robust and well-understood. In our thought-experiment, boundary layer friction is controlled by the prescribed $\overline{\mathcal{F}}$ aloft. In Fig. 1a the whole response — including meridional circulation and boundary-layer friction — would die out if the waves were switched off. We agree that none of this is obvious from inspection of C's (2) and (3).

Postscript

We take the opportunity to remind the reader that, as pointed out by Rosenlof and Holton (1993), Fig. 13 of HMMSS should not be overinterpreted near the zero contours in Fig. 12 of HMMSS. Fig. 12 showed an estimate W of mean vertical velocity $\overline{w}^*$ in the real lower stratosphere, and Fig. 13 estimated the overlying altitude range from which wave-induced forces exert significant control over $\overline{w}^*$. This should be regarded as an overestimate near the zero contour, because the estimate was based on fractional and not absolute error. But the overlying altitude range can still be substantial. For instance, Garcia and Boville (1994) find that "gravity wave drag in the mesosphere affects the state of the polar winter stratosphere down to altitudes below 30 km."

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FIGURE CAPTION

Figure 1. (a) Simplified extratropical Earth-atmosphere model that conserves its total angular momentum (see text). Dashed curves represent upward wave propagation from an idealized frictionless, quasi-orographic wave source. The wave-induced force on the atmosphere is confined to the shaded region aloft. (b) The same situation, shown without explicit reference to the waves. (c) The causally incorrect "upward" response predicted by an injudicious use of C's Eq. (3).