ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 34, OCTOBER 2017, 1150–1158

• **Review** •

On Multi-Level Thinking and Scientific Understanding

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(Received 21 November 2016; revised 19 January 2017; accepted 20 January 2017)

ABSTRACT

Professor Duzheng YE's name has been familiar to me ever since my postdoctoral years at MIT with Professors Jule CHARNEY and Norman PHILLIPS, back in the late 1960s. I had the enormous pleasure of meeting Professor YE personally in 1992 in Beijing. His concern to promote the very best science and to use it well, and his thinking on multi-level orderly human activities, reminds me not only of the communication skills we need as scientists but also of the multi-level nature of science itself. Here I want to say something (a) about what science is; (b) about why multi-level thinking—and taking more than one viewpoint—is so important for scientific as well as for other forms of understanding; and (c) about what is meant, at a deep level, by "scientific understanding" and trying to communicate it, not only with lay persons but also across professional disciplines. I hope that Professor YE would approve.

Key words: communication skills, cross-disciplinary communication, scientific understanding, unconscious assumptions, multiple viewpoints, brain hemispheres, biological evolution

Citation: McINTYRE, M. E., 2017: On multi-level thinking and scientific understanding. *Adv. Atmos. Sci.*, **34**(10), 1150–1158, doi: 10.1007/s00376-017-6283-3.

1. Introduction

I want to thank the organizers of the Symposium, and of this Special Issue, very much indeed for the invitation to participate. I count it a great honor. However, I was a little hesitant about accepting at first because, although Professor YE's early work, on jetstreams especially, was an important precursor to my own later work on that topic, our research pathways took us mostly through different specialities—including, of course, climate science and Earth system science in his case.

I did want to show Fig. 1, though, from one of Professor YE's early papers (Yeh, 1950a). That was the first of a series of pioneering works showing the huge effects of the Tibetan Plateau on large-scale atmospheric circulations, work that continues today under the leadership of Professor Guoxiong WU. Figure 1 is a well resolved cross-section, from rawinsonde data, of wind speed in a winter jetstream over China near 120°E. The wind speed in the jet core was well over 50 ms^{-1} in this case. Further east, the jet was stronger. The data were sparse by comparison with today. Despite that sparseness YE was able to show the jet structure very well, by cleverly taking advantage of the way the Tibetan Plateau stops the jet from unsteadily meandering too much, so that it is almost a steady, or stationary, flow.

And that, of course, is interesting and remarkable in itself because, as everyone knows, strong terrestrial jetstreams love to meander extensively, and in ever-changing ways, under the influence of a global-scale web of teleconnections. That meandering, by the way, makes them very different from the strong prograde jetstreams on the planet Jupiter (e.g. Thomson and McIntyre, 2016; and references cited therein). By comparison, Jupiter's jets hardly meander at all. They follow latitude circles closely. There is a myth, or unconscious assumption, that all jet systems have the same dynamics, but I now think that it is simply wrong. But that is another story. I won't say much about jets here. Instead, I want to widen the perspective, and comment on the nature of science itself, and on the problems of understanding and communicating it. As the newsmedia continually remind us, these problems are far from trivial.

Science, of course, is an amazing and wonderful thing. Surely it is one of our best hopes for future civilization. When I met Professor YE in 1992, in Beijing, my strong impression was that he felt the same way about science. Furthermore, Professor YE struck me as being what in English we call a perfect gentleman, someone who represented human civilization at its best. And of course his name is well known as someone influential in the cause of good science and of using it well—not least in tackling the increasingly urgent problems of climate change, as Professor Congbin FU reminded us in his conference talk (Fu, 2016).

So I am glad I had a chance myself to meet Professor YE. He was a great man as well as a charming host. And it was interesting to meet someone who had worked in Rossby's group

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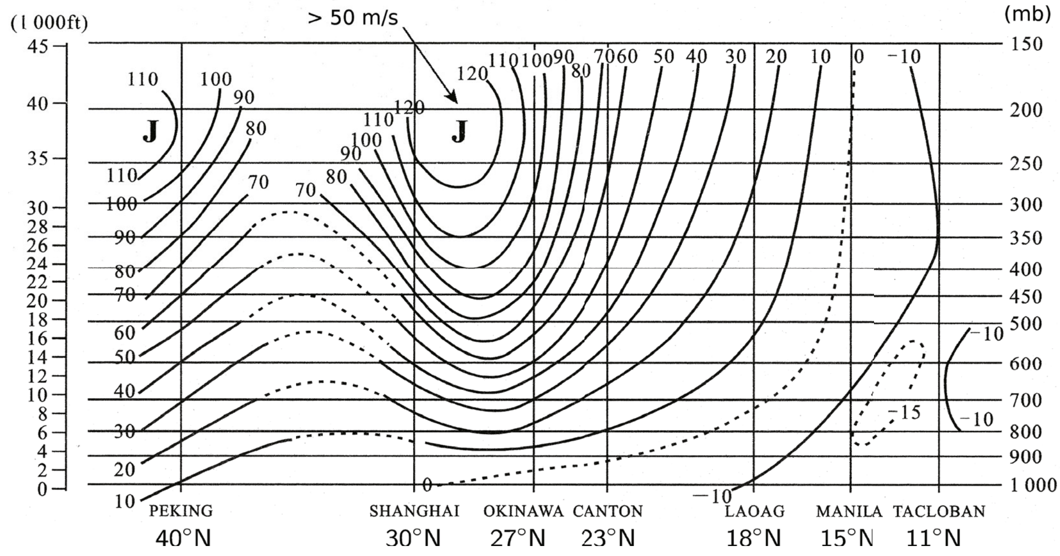

Fig. 1. Cross-section of wind speed in a winter jetstream over China near 120°E, from rawinsonde data. The wind speeds are shown in the old American units of miles per hour (1 mile = 1609.34 m, so that 120 miles per hour = 53.64 m s^{-1}). Data are from December–January 1945–1946. [Reprinted from Yeh (1950a)]

so long ago, and whose work since then covered such a wide range in atmospheric science, in climate science, and indeed in psychology and sociology with his thinking on multi-level orderly human activities.

And it hardly needs saying, especially to this audience, that understanding our planet's life-support system—and learning to treat it more sympathetically through orderly human activities—is one of the most difficult and important challenges confronting us as civilized human beings. It is a challenge both to our science and to our communication skills within, across, and outside our different specialities. Even the purely scientific aspects, as one might call them, are dauntingly complex as everyone knows.

So here I would like to step back and say something about what science is, in all its branches, physical, chemical, mathematical, biological, psychological,... and something about how it can hope to deal with complexity as well as how to communicate it. That is difficult in a short article. But in case you find any of it interesting there's an e-book that you can find on the internet, for instance by websearching with the strings "e-book" and "lucidity principles", where I try to develop these themes more fully with suitable backup from the research literature.

2. Science and complexity

One of the most surprising, indeed astonishing, things about science is how often it manages to deal with what looks like hopeless complexity at first sight. It is astonishing, for instance, that data assimilation and weather forecasting work as well as they do, despite the so-called butterfly effect, to say nothing of the importance of subgrid cumulus convection and so on. Of course such complexity was nothing new to Professor YE, and it is nothing new to any of us who have worked in any part of the Earth sciences. The Antarctic ozone hole, whose fluid dynamics I was concerned with in my own research, is another example of what looks like hopeless complexity at first sight.

(Think of the range of time scales! Time scales go all the way from femtoseconds, as photons hit molecules, through seconds, minutes, hours and days out to many decades for the phenomenon as a whole. And the spatial scales similarly range from atomic out to global or planetary scale, the scale of the mean circulations that carry molecules on epic journeys, e.g. Fig. 2. The significant radiative, photochemical, and fluid-dynamical processes interact nonlinearly across the entire range of space scales and time scales. The fluid dynamics giving rise to the circulation in Fig. 2 is very complex in itself. It includes jetstream dynamics and can be viewed as a highly nonlinear, highly inhomogeneous "jigsaw puzzle" of fast and slow waves and turbulence, for which standard homogeneous turbulence theory is not much use.)

Yet, despite all this complexity, enough was understood, with strong enough cross-checks, to give us a remarkably secure understanding. It was secure enough to defeat a well-funded disinformation campaign and to become influential in commercial and political decision-making. This was the first time a human-induced global-scale environmental change was taken seriously by big business and governments. And the result was the ongoing Montreal Protocol, with its provisions for repeated updating, together with the important side benefit of reducing the total burden of greenhouse gases. As pointed out for instance by Ye et al. (2003)[a], that was a wonderful example in which not only the science but also the orderly human activities succeeded, increasing our hopes for the further such successes that are now so urgently needed, and now made more likely by the similarly-structured Paris Agreement on climate change and its ratification by China

[a]I understand that there is a prior publication on this topic in Chinese (Ye et al., 2001).

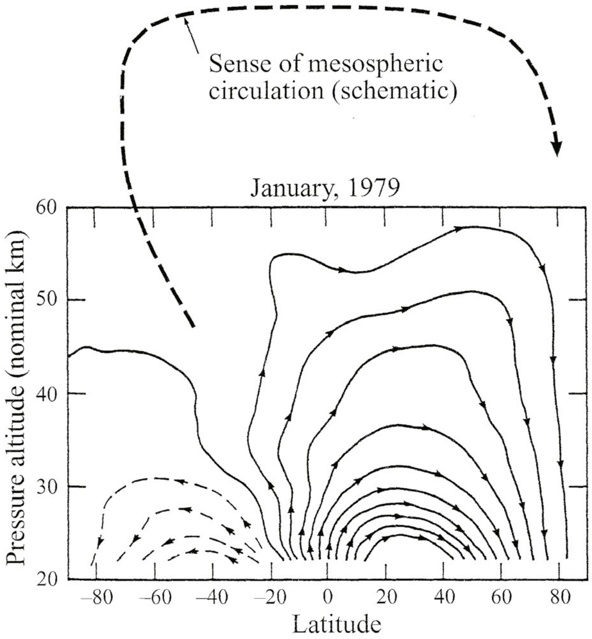

Fig. 2. Mass transport streamlines of the stratospheric transformed Eulerian-mean circulation for January 1979 (light dashed and solid curves). [After Solomon et al. (1986). ©American Meteorological Society. Used with permission.] This is a quasi-Lagrangian measure of the zonally averaged circulation that is both practical to compute and directly relevant to the global-scale transport of ozone, chlorofluorocarbons, and other chemical species. It was computed from a homogeneous satellite radiometer dataset (LIMS) and a state-of-the-art radiation scheme. The nominal altitude scale is based on an *e*-folding pressure scale height of 7 km. The heavy dashed streamline (schematic only) indicates the qualitative sense of the mesospheric branch, deduced from other observational evidence such as the existence of noctilucent ice clouds at altitudes ~ 83 km despite the photolytic destruction of water vapor there. The large-scale upward velocity at bottom centre ~ 0.2 mm s^{-1}, about a scale height a year. This velocity is far too tiny to be observed directly. However, an independent cross-check came later from the discovery of the "tape-recorder effect". The annual cycle in water vapor and methane is imprinted on the rising motion like the signal on a magnetic tape and shows upward velocities of the same order.

and the USA. There can be no doubt that Professor YE had a key role in raising the Chinese government's support for climate change studies, which in turn provided sound scientific advice in the developments leading to the Paris Agreement and its ratification by China.

3. Science and multi-level thinking

In science, as such, multi-level thinking is of course about recognizing and using different levels of description, as distinct from the different levels of organization and cooperation needed for orderly human activities. And the need for such multi-level thinking is almost the first thing one has to recognize, when trying to deal with any degree of complexity in a scientific problem.

There is nothing new about this. It has always been important in science because, obviously, what is complex at one level can be simple at another, and what is complex from one viewpoint can be simple from another. Scientific progress has always, throughout its history, depended on finding a level of description and a viewpoint—or viewpoints, plural—from which something at first sight hopelessly complex becomes simple enough to be understandable. My favorite example is Isaac NEWTON. He treated the Earth as a point mass.

Of course NEWTON knew that the Earth is a much more complicated object than a point mass, or even a spherically symmetric body. But the point mass and the spherically symmetric body were good levels of description to use for his particular purpose, which was trying to understand planetary orbits, with the added bonus that the two levels are mathematically equivalent for that purpose.

In the ozone-hole problem, the quantum-mechanical details of photons hitting molecules are complex. But we usually go up a level, considering large numbers of molecules in local thermodynamic equilibrium. The description is not only far simpler at that level, but more than accurate enough within the stratosphere. Indeed, it is much more accurate than some of the other simplifications we make, such as using broadband spectra in shortwave and longwave radiation schemes, and various simplifications in the fluid dynamics. (There, as in data assimilation and weather forecasting, we often simplify, at least conceptually, by using so-called balanced dynamics. Either we neglect sound waves and gravity waves altogether, or we include gravity waves only for their cumulative mean effects on the isentropic distributions of potential vorticity.)

All this is familiar and maybe obvious; and as I said, we in the Earth sciences use multi-level thinking all the time. But the need for it seems to me to be worth some emphasis, in the wider context of this discussion, if only because of the long tradition in some of the sciences—a tradition that is sometimes far too influential, I think—saying that lower levels are always more important than higher levels. This is called reductionism, trying to focus on the most basic and elementary "units". It has had many successes and can still be very useful. But the trouble comes when it takes an extremist form, being seen as the Answer to Everything, and the Only Possible Viewpoint. In biology, for instance, it has led to the strangely persistent idea that genes are more important than all the many higher levels, beginning with the molecular-biological "circuits" or "networks" that switch genes on and off—for instance involving those clever protein molecules that act like transistors (allosteric enzymes)—so I am firmly with those who work on the "systems biology" aspects, recognizing that the higher levels in all their complexity are equally important, and deserving of equal status.

To put it more sharply, multi-level thinking is worth emphasizing as a necessary antidote to extreme reductionism, including the "genes' eye view" in biology, sometimes called the "selfish gene" approach, which says that genes govern everything but which, we now know, misses many crucial aspects of how organisms and ecologies work, not least the fact that causal influences across levels act downward as well as upward. I refer to recent, cutting-edge work on this in my e-book.

4. Perception, understanding, and the unconscious

I want to make another point about multi-level thinking. It is much more than just something to cultivate consciously. It is already present in our unconscious mental processes. One might say that multi-level thinking is instinctive. I use the word "instinctive" in its everyday sense referring to things we do, and perceive, and feel automatically, ahead of conscious thought.

In other words, multi-level thinking is something completely natural, already built in to the way our brains work including, for instance, the left and right hemispheres with their different roles. Our understanding of those roles has progressed far beyond the usual caricature in popular culture. Our brain hemispheres give us at least two levels straight away, ahead of conscious thought. I'll come back to that point in section 6 but, to tempt you to read on, I'll just quickly say that that, in turn, gets us closer to what science is, and what scientific understanding is, in a deep and fundamental sense.

What, then, is this thing we call "understanding"? Well, to start with, it is bound up with the way perception works. In English, at least, we often use the words "perception" and "understanding" to mean almost the same thing, especially at an intuitive level.

If I perceive—visually, auditorily, and seismically—a charging rhinoceros coming at me, then I understand—quickly, intuitively, and ahead of conscious thought—that I should jump out of the way, for otherwise I might come to a sorry end!

So the way perception works is important, and is tightly linked to the way understanding works, especially at intuitive levels. And all this makes sense in terms of biological evolution. It is evolutionarily ancient. It is and has been central to survival, of ourselves, of our ancestors, and of other creatures, for hundreds of millions of years.

And for us today it is central to practically everything we do. It is central to the sciences, to the arts, and to all sorts of thinking skills. It is central to communication skills of any kind, scientific, artistic, and personal. It is central to how music works, and mathematics too. It is central to promoting orderly human activities.

Again, you might say that most of this is obvious. But what is not obvious, I would suggest—and you can see it quite plainly in the professional literature on philosophy—is the way perception works.

Here is an example to show what I mean. It is a classic in experimental psychology, from the work of Professor Gunnar JOHANSSON in the 1970s. To appreciate it, you need to watch an animated version of the left-hand image in Fig. 3, which consists of twelve dots. If you have a smartphone with a web browser linked to a QR reader, you should be able to see the animation by pointing the smartphone at the right-hand image. The figure caption gives some alternative ways to see the animation.

As soon as the twelve dots start moving, everyone with normal vision sees a person walking. This immediately illustrates several things. First, it illustrates that we all make unconscious assumptions. Here, we unconsciously assume a particular kind of three-dimensional motion. In this case the unconscious assumption is completely involuntary. We

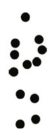

Fig. 3. The left-hand image with its twelve dots is a single frame from Gunnar Johansson's classic "walking lights" animation. The animation (by kind courtesy of Professor James Maas) can be seen in the supplementary material for this paper or by pointing a smartphone with a QR reader at the right-hand image, which represents the URL or web address http://www.atm.damtp.cam.ac.uk/people/mem/walking-lights.html. Another way is to websearch with "walking lights" "Gunnar Johansson".

cannot help seeing a person walking, despite knowing that it is only twelve moving dots.

The animation also shows that we have unconscious mathematics, Euclidean geometry in this case. In order to generate the percept of a person walking, your brain has to fit a mathematical model to the incoming visual data, in this case a mathematical model based on Euclidean geometry. (And the model-fitting process is an active, and highly complex, predictive process most of which is inaccessible to conscious introspection.)

This brings me to the most central point in our discussion. Science does essentially the same thing. It fits models to data. So science is, in the most fundamental possible sense, an extension of ordinary perception. That is a simple way of saying what was said many decades ago by great thinkers such as Professor Sir Karl POPPER.

Another way to say it is that science can reasonably be called a quest for truth but is never about absolute truth, and never about absolute proof, despite what many people think. It is always about models and how good they are—how simple, how accurate, how widely applicable, and subject to how much cross-checking. Even a candidate Theory of Everything, so-called, embracing quantum mechanics and general relativity, could never be tested against observation with infinite accuracy and over an infinite domain of applicability. So the question of whether it is indeed an Absolutely True Theory of Everything—with "everything" understood in an extreme reductionist sense—is one of many questions that lie outside the scope of science.

There are of course believers in the possible Absolute Truth of such a theory just as, for over two centuries, there were many believers in the Absolute Truth of the mathematical model we call Newtonian mechanics. Albert EINSTEIN's discoveries, growing out of the contradiction between Newtonian mechanics and Maxwellian electrodynamics, were profoundly shocking, and confusing, to such believers. The confusion disappears, however, as soon as one sees that science is about model-fitting and cross-checking. Making this point is much more than a philosophical luxury, because it helps us to get past some of the confusion, in the newsmedia and in popular culture, about the nature of science and about its power and its limitations.

5. Music, mathematics, and organic change

Before we leave the subject of the walking lights animation, there is a separate point worth noting that the animation also illustrates. It is worth noting because it has great practical importance for communication skills. It says that we are perceptually sensitive to organic change—to patterns in which some things change continuously, or by small amounts, while others stay unchanged, or invariant. This statement may be called the "organic-change principle".

The unconscious internal model evoked by the walking lights animation exhibits organic change. It is an organically-changing three-dimensional pattern. The invariant elements are the number of dots, and the three-dimensional distances between some of the pairs of dots in the internal model. There are good biological reasons for our perceptual sensitivity to organic change. One such reason is that it helps to distinguish living things from dead things. That is plainly important for survival.

Our sensitivity to organic change shows itself in many ways, for instance in the way music works. Music consists mostly of abstract sound patterns that change organically, over a range of time scales. Our brains love to play with such patterns for their own sake.[b] Mathematics exists for similar reasons. For instance there are many beautiful theorems in mathematics that identify "invariants", quantities that stay the same while everything else changes, often within an infinite space of possibilities. And skilled communicators use organically-changing word patterns. The invariant elements clarify and strengthen the message.

A simple example is the English sentence "If you are serious, then I'll be serious." The invariant element "serious" makes the sentence clearer and stronger than alternative versions such as "If you are serious, then I'll be also." That kind of strengthening works in any language I have ever looked at. I am ashamed to admit that I do not write or speak any of the Chinese languages, but even I can see that there is an invariant element playing a similar role in the following rough translation of "If you are serious, then I'll be serious."

你若当真, 我便当真。

For comparison, a version without the invariant element is the following, which is more like "If you are serious, then I'll be also."

你若当真, 我也会。

I am assured by my Chinese colleagues that the version having the invariant element is clearer and stronger, just as in English. That is only one example, among countless others, of how the organic-change principle can help us with

[b]For anyone familiar with the magic of musical harmony, there is an interesting point about the way harmony exploits the organic-change principle. Besides the invariant elements, such as some pitches staying unchanged, powerful harmonic progressions or chord sequences use pitch changes that are small in either of two quite different senses. An octave leap is small in one sense, and a semitone step—adjacent notes on the keyboard or fingerboard—is small in the other. The perfect-fifth leap and the whole-tone step are the next smallest, in the first and second senses respectively. So with musical harmony one can generate a feeling of going somewhere that is both nearby and, at the same time, far away, as with the so-called hyperspace of science fiction stories. (Smallness in the first sense comes from the structure of the harmonic series of overtones. The unconscious brain's internal models need to take account of that structure to enable "auditory scene analysis", which can be important for survival—the identification of sound sources within "a jungleful of animal sounds". Among the data to which the internal models are fitted are the quasi-periodic signals from a larynx or a syrinx. Contrary to what books on musical acoustics say, the computations involved in accurate pitch perception are mediated by neural circuitry and take place in the time domain. However, the whole process can be viewed in the frequency domain through Fourier transformation, from which the harmonic-series structure emerges.)

communication skills. And the more complicated the subject matter, the more critical it becomes to take full advantage of the organic-change principle alongside other "lucidity principles", such as omitting needless words, maintaining coherent ordering, and being more explicit than one feels necessary.

6. Unconscious mathematics and the brain hemispheres

Coming back to science and multi-level thinking, let me summarize the key points so far. They are that science and ordinary perception both work by fitting models to data, that unconscious assumptions are involved, and that we all have unconscious mathematics and unconscious multi-level thinking. One reason for the latter is that we have two brain hemispheres, though there are other reasons as well.

Regarding mathematics, not only do we have unconscious Euclidean geometry but also, for instance, unconscious calculus. If you stare at Fig. 4 for a few seconds, and if you have normal vision, you will see a beautifully smooth curve joining the inner ends of the black segments. The smooth curve is not actually present on the screen or on the paper. It is constructed by your visual system, ahead of conscious thought. This is another classic in experimental psychology. Such curves are called illusory contours.

The mathematics for constructing such curves is the calculus of variations, in which some norm measuring curve roughness is minimized, over all the possible curves joining the ends of the segments. So Fig. 4 shows that we have unconscious calculus of variations, with an unconsciously-chosen norm. More generally we also have, very probably, unconscious Bayesian inference with priors that are unconsciously chosen, mediating our perceptual model-fitting processes. In many instances the priors are variable and context-sensitive.

Now a fundamental point about the brain hemispheres, from today's knowledge of them, is that they specialize in two very different styles of model-fitting that show us different aspects of what is perceived. Those styles might be called "dissected" versus "holistic". I discuss them in my e-book, with reference to the important recent work of Dr Iain McGILCHRIST and Professor Vilayanur S. RAMACHANDRAN. Both styles are important to survival, and are evolutionarily ancient. They give us two very different levels of description, operating unconsciously: a lower level that dissects fine details and a higher level that is more holistic and, in addition, more open to the unexpected. For most people these lower and higher levels are specialities of the left and right hemispheres, respectively, though the other way round for some individuals. Extreme reductionism in science might be called extreme dissectedness, with one hemisphere—as it happens, the hemisphere that does the talking—dominating the other.

These two levels show up again and again in mathematics. Take analytical geometry for instance. It focuses on the relevant algebraic symbols and equations, and on detailed symbolic manipulation, giving a precise but rather dissected view. By contrast, a more directly visual approach allows us to grasp overall spatial relations, though often in a less precise way. That is a more holistic level. Paying attention to both these levels of description can deepen our understanding of a geometrical problem.

Similarly, the most powerful, versatile, and innovative scientific thinking uses varieties and hierarchies of models including precise mathematical models and computer codes in partnership with "conceptual" models that are fuzzier, more intuitive, and often not overtly mathematical—perhaps expressed more in words or pictures or even in intuitive feelings. Quite often, the intuitive models are wrong or partly wrong to begin with, until modified as a result of cross-checking against something more precise.

Such variety and cross-checking within the repertoire of models has its counterpart—a wholly unconscious counterpart—in so-called ordinary perception. Think about crossing a busy road. Neuroscience has revealed a variety of specialized internal models or model components that represent different aspects of complex visual scenes. There are separate model components representing not only fine, sharply-focused detail on the one hand, and fuzzier overall spatial relations on the other, but also, for instance, color and motion. For instance damage to a part of the brain dealing with motion can produce visual experiences like successions of snapshots or frozen scenes, such as the left-hand image in Fig. 3. Crossing the road becomes impossibly dangerous.

A corollary of the above is that, in order to release the full power of our conscious and unconscious multi-level thinking, it is helpful to cultivate the habit of looking at

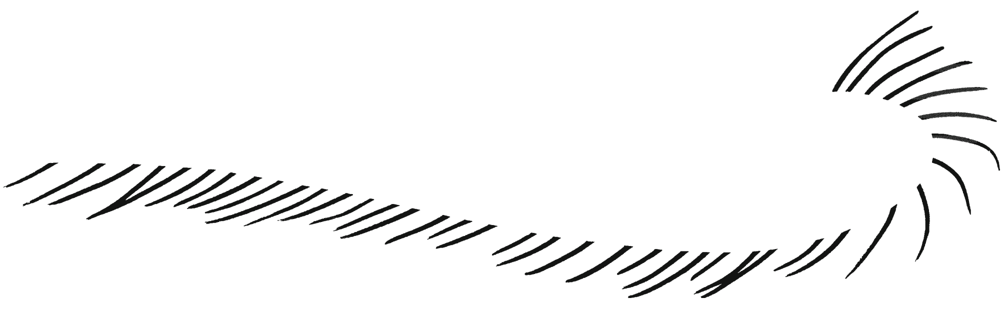

Fig. 4. The illusory contour joining the inner ends of the black segments demonstrates our unconscious calculus of variations.

a problem from more than one viewpoint. It helps us to ask the right questions. It widens the repertoire of models and model components brought into play—conscious and unconscious—and increases the chance that each brain hemisphere contributes fully and plays to its strengths. For instance the fluid-dynamical jigsaw presented by jetstreams and the ozone hole is far too complicated, and far too nonlinear, even to begin to understand from one viewpoint alone. One needs equations, computer codes, pictures, words, and feelings too—imagining forces, constraints, and reactions, including remote reactions via the pressure field. Gleick (1992, pp. 131 and 244–245) vividly describes how the great physicist Richard FEYNMAN cultivated just such a plurality of viewpoints. If one can bring the different views into agreement with each other wherever they overlap, repeatedly cross-checking one view against another as well as, of course, against experiment and observation, then one has attained a deeper and more accurate understanding, including aspects of the problem that may at first seem counterintuitive.

A good example of such counterintuitiveness is Victor STARR's "negative viscosity" and the self-sharpening of jet velocity profiles. That of course is part of why the great atmospheric jetstreams are so persistently river-like, along with their oceanic counterparts such as the Gulf Stream and the Agulhas and the Kuroshio. Professor YE's early papers, such as Yeh (1950b), contain some of the first hints as to how this works, pointing toward today's understanding in terms of the strange and remarkable properties of potential vorticity and its tendency to mix along isentropic surfaces, on either side of the jet core.

7. Three unconscious assumptions: a cautionary tale

The final point to make is obvious, but is often of critical importance in science. Unconscious assumptions or mindsets can, of course, be wrong, and can greatly impede progress. And by the way, another thing we know about the two brain hemispheres is that the hemisphere that specializes in finely-dissected, finely focused, analytic styles of perception, including detailed symbolic manipulation—usually the left hemisphere—is the hemisphere most prone to mindsets. That is the downside of its analytical power, its special ability to zoom in and grasp precise details. It is sometimes called the steel-trap mind. All this should further motivate us to cultivate taking more than one view of a problem. "There's no point in being quantitatively right if you're qualitatively wrong."

I want to finish by recalling three examples of wrong unconscious assumptions that I came across during my research career. The first two are central to atmospheric and climate science. I am sure Professor YE would have recognized them. They are from past history and not, as far as I know, problematic today. But I think they are instructive. The third is from biology. Professor YE might have recognized this third example as well, if only because it has greatly impeded progress in understanding our own human nature—for one thing misinterpreting and distorting what Charles DARWIN said on that topic—and it still impedes progress today, sometimes quite severely. Of these three assumptions at least the first two must, I feel sure, have been unconscious, because their wrongness becomes so obvious as soon as they are made conscious. As for the third, I must leave it to my biological colleagues to assess it.

Assumption 1: correlation implies causality. This also comes in a harder mathematical version, which I sometimes call the "$A = B$ assumption" and which is actually the form of it that I myself have encountered most closely. It says that when you have an equation $A = B$, implying of course that a variable A is perfectly correlated with another variable B, it also implies that B causes A, or that B drives A. That assumption can be seen as obviously wrong, indeed silly, once it is made conscious, because one can equally well write the equation as $B = A$. I suspect that there might be an unconscious tendency to confuse the equation $A = B$ with a line of computer code $A = B$, which looks the same but means something quite different.

One counterexample would be slowly pushing a dinner plate along a table. To a good approximation one has a balance between the applied force A and the friction force B. But it makes no sense to say that B causes A. You may laugh, but when working on the ozone problem I encountered a closely similar assumption, again and again, about what causes global-scale circulations like that in Fig. 2. They are thermally driven, it was argued, because to a good approximation we have an equation $A = B$ in which B is a mean diabatic heating rate, and A is the static stability times the transformed Eulerian-mean vertical velocity. The trouble with the argument is that, because of the way infrared radiative cooling works, the stratosphere is a thermally-relaxing system. This means that B has a role rather like the friction on the dinner plate. So it is best regarded as part of the response to whatever is driving the circulation, which turns out to be more aptly described as a mechanical pumping action due to wave-induced angular momentum transport. That pumping action has been thoroughly studied using a hierarchy of conceptual, analytical, numerical, and fluid-laboratory models. It can usefully be called "gyroscopic pumping" as a reminder that Coriolis effects are crucial. "Ekman pumping" is a special case of it.

Assumption 2: small implies unimportant. That too is obviously wrong once you make it conscious because, again, it is so easy to find counterexamples. One of these is the ordinary audio amplifier. The small input signal is important. Yet, especially during the first half of my career, I repeatedly encountered a mindset that seemed to be a version of Assumption 2. It was the idea that energy budgets are the Answer to Everything, "the" way to understand how the atmosphere works. For an audio amplifier, the implication would be that only the output stage and the large currents from the power supply are important, the input signal being so tiny that its effects must quite obviously be negligible.

Again, you may laugh, but think again about the ozone hole, and the well-funded disinformation campaign that tried to discredit the science we did. Some of the campaigners had impressive-looking scientific qualifications. Yet one of the arguments they used was that the amounts of chlorofluorocarbons in the atmosphere are so tiny by comparison with the amount of ozone that the chlorofluorocarbons couldn't possibly be important, and therefore need not be regulated. Of course most of us can clearly say why that argument is wrong. An amplifier mechanism is involved. It is called chemical catalysis.

I think most of us also recognize that the climate system is an amplifier, albeit slowly-responding, very noisy, very nonlinear, and fearsomely complex. The input signals include small injections of CO_2, and small changes in the Earth's orbit. The response, over long time scales, is huge. It is well known and thoroughly cross-checked that sea levels have gone up and down by as much as 120 m or so, in the late Pleistocene. (And it bothers me that people often talk about "the" climate sensitivity to CO_2, with no mention of the many nonlinearities that are suppressed in model experiments but not in the real climate system—producing many different sensitivities over different time scales, some of which are so long, relative to human societal time scales, that the changes due to human activities are effectively permanent and irreversible.) In my e-book I try to promote an "amplifier metaphor for climate," and to point out that the human-induced CO_2 input signal should be measured not against total atmospheric CO_2, as is usually done, but more appropriately against the natural range of variation of atmospheric CO_2, ~ 100 ppmv, which shows up so clearly and unequivocally in late Pleistocene ice-core records.

Assumption 3: dynamical mechanisms having disparate timescales cannot interact strongly. I call this the multi-timescale fallacy. Its wrongness should be obvious because, again, counterexamples are so easy to find, and so plentiful. The ozone-hole and climate problems are very clear counterexamples, as well as all the wave–mean interaction problems I have worked on. And there are others far simpler. Perhaps the simplest is gas pressure and temperature. When you pump up your car or bicycle tyres, the changes in pressure and temperature are exceedingly slow by comparison with the fast molecular collisions involved. The slow–fast interaction is all-important.

So it was strange for me to discover, in my studies of the biological research literature, discussed at greater length in my e-book, and in my conversations with leading biological researchers, that Assumption 3 is very commonly made. It shows up, for instance, in the literature on evolution, including that on the evolution of our own ancestors. And yet there is, for instance, a powerful case (starting with linguistic studies in Nicaragua) that human evolution, including the development of our language ability, must have depended on strong interactions between very slow and very fast processes, violating Assumption 3—in particular slow genomic evolution and fast cultural evolution.

The possibility that there could be strong slow–fast interactions of this kind seems to have gone almost unrecognized in the literature on biological evolution, with a few exceptions such as the writings of the great paleoanthropologist Phillip TOBIAS. Indeed, one often reads heavy warnings against confusing the slow with the fast, as if it were self-evident that the two could not possibly interact. This is sometimes designated as confusing "ultimate causation" (slow) with "proximate causation" (fast). It is like saying that just because gas pressure changes are so slow, and molecular collisions so fast, they must be considered as completely separate processes with no significant interaction. The related assumption that genes govern everything—motivating the choice of the word "ultimate"—is even worse, if anything, like saying that slow pressure changes govern fast molecular collisions, with no back-reaction the other way.

8. Concluding remarks

These examples are perhaps useful reminders of why multi-level thinking and multiple viewpoints are so important as we face tomorrow's increasingly complex problems—and why communication skills are so important, for instance across scientific disciplines. My third example reminds us especially clearly of the value of cross-disciplinary communication, and in particular of how valuable it can be to understand even a few of the most basic things from a field of science outside one's own speciality. The great physicist Max BORN had a wonderful phrase that captures some of this. He talked about the loosening of thinking (Lockerung des Denkens) that lets us see things in new ways.

And what about that most complex of all phenomena, human nature? It is something that Professor YE seems to have understood very well. And multi-level thinking is crucial to such understanding. It is crucial, for instance, to blowing away the confusion surrounding ideas such as "self", "consciousness", and "free will". Much of that confusion comes from mixing up different levels of description. It seems to me that that is worth thinking about.

Acknowledgements. Professor Jianhua LÜ and Dr Yixin WAN kindly helped me with the Chinese sentences displayed above, as did Ms Zheng LIN and Ms Xüejing LOI. Professor LÜ also gave valuable help with several other aspects of the lectures I gave in China. I want to thank especially Professors Jiang ZHU and Song YANG, respectively, for their kind invitations to speak in this Symposium and at the Guangzhou and Zhuhai campuses of Sun Yatsen University. For kind and generous hospitality, and further sponsorship, at Nanjing University and at the Institute of Atmospheric Physics in Beijing, I want to thank also Professors Yimin LIU, Zhemin TAN, and Guoxiong WU. Professors WU and Congbin FU advised me on matters concerning the Paris Agreement. A referee, Dr Paul WILLIAMS, kindly made useful suggestions for improving this article.

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