Climate change: the role of plant physiology

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The year 2011 will mark the completion of 150 years since John Tyndall’s paper ‘On the absorption and radiation of heat by gases and vapours’, which probably heralded the beginning of scientific study regarding global warming and climate change. It is almost 90 years since another precursor of modern climate studies, a model for weather forecasting, was proposed by Richardson (1922) and 50 years since the first global atmospheric models were designed. Models and methods for studying climate change are constantly being improved and newer dimensions are being added to the existing models, making simulations and predictions more realistic and reliable. Recently, the extent to which plant physiology affects warming over land, surface run-off and other climatic factors was estimated by Cao et al. They performed a 100-yr simulation of doubling CO₂ concentration using the National Centre for Atmospheric Research (NCAR) coupled Community Land and Community Atmosphere Model version 3.5, and found that physiological forcing (that is, the effect due to reduced transpiration of land plants) causes an increase of 0.42 ± 0.02 K in mean surface air temperature over land, compared to an increase of 2.86 ± 0.02 K due to radiative forcing (the effect due to trapping of longwave radiation; see Figure 1). Physiological forcing also causes an 8.4 ± 0.06% increase in global surface run-off, which is 65% of the total increase in surface run-off due to climate change. Thus, Cao and co-workers established that the physiological effect of CO₂ plays a much larger role in global warming and climate change than was anticipated before.

CO₂ is a unique greenhouse gas – it is probably the only one which has a major role in plant physiology. Increased levels of CO₂ can cause the stomata of the plants to close partially. This in turn reduces transpiration, which ultimately influences climate change. Climate response to reduced evapotranspiration due to increased CO₂ concentration, in terms of land-surface warming, changes in humidity, cloud cover, etc. has been the subject of many earlier studies. For instance, in 1999, a simulation was conducted by doubling the concentration of CO₂, and a minor increase in temperature and a slight decrease in precipitation were observed. Another study in 2000 analysed the effect of reduction in transpiration on the amount of soil moisture and precipitation. Recent studies have reiterated the accepted stance that CO₂ radiative forcing plays a more important role in global warming than physiological forcing. These studies recognized that reduced evapotranspiration would weaken the hydrological cycle and thus cause an elevation in temperature, but they did not provide an accurate quantification of the elevation in temperature that CO₂ physiological forcing would lead to, nor did they recognize the full import of the effect of plant physiology on climate.

The paper by Cao et al. discusses the role of physiological forcing on various aspects of climate change, such as global warming and hydrological cycle, based on simulations using a newer, improved model. Talking to me about the effect of reduced evapotranspiration on global warming, one of the authors of the paper (G. Bala) mentions, “We came to the conclusion that it is about 14% when compared to the greenhouse effect. It is small, but it is not negligible – it is not 1%. It is substantial”. It was also found that over the ocean surface, CO₂ physiological forcing causes 7.5% of the total warming. A previous study by the same group, using Community Atmosphere Model (CAM 3.1) and Community Land Model (CLM 3.0) had shown a mean warming of only 0.1 K over the land surface. With the improved 3.5 version of the model, they have found that physiological forcing in fact causes an increase in temperature of 0.42 K. ‘We noticed in our previous study that there was a deficiency with the earlier version of the model, which was related to transpiration. We compared many models and what we found was that nearly 40-45% of the water flux over land comes from plant transpiration. The rest comes from the soil and water stored in the canopy. The earlier version of the model actually had grossly underestimated the water flux from plant transpiration – we just had something like 5% of the total evapotranspiration over land’, explains Bala.

Another aspect that was underestimated was the effect of physiological forcing on surface run-off. Studies with the previous version of the NCAR model showed only a negligible role for physiological forcing in changes in the hydrological cycle. A study in 2007 using the UK model, HadSM3, had recognized that the effect of physiological forcing might

Figure 1. Percentage warming due to CO₂ physiological effect on plants. Source: http://www.lsc.ernet.in/research_cs/2globalwarm.html
be equivalent to that of radiative forcing in increasing continental run-off. In closer agreement with the UK modelling study, Cao et al. show that physiological forcing increases surface run-off by about 8.4%, much greater than the effect of radiative forcing, which is about 5.2%. ‘Even though the warming effect was only 14% when compared to the greenhouse gas effect, the effect on surface water run-off was actually 65%. Only 35% was due to greenhouse gas effect. People mostly look at temperature change; but under climate change, there are also other components of the climate system which are equally important. Surface water run-off is one such. You can see that in this case, the physiological effect actually has more effect on the water cycle than the radiative effect’, mentions Bala. The group found that the effect on run-off varied from region to region, with some regions such as the eastern Amazon basin even showing a decrease in surface run-off due to CO₂ physiological forcing as a result of reduced precipitation.

A unique aspect of the findings by Cao et al. is the heterogeneous nature of the effect of plant physiology on climate. The simulations show that in 19.2% of the land surface, including regions like the boreal forests, parts of Amazon and South Africa, more than 20% of the total surface warming is caused by CO₂ physiological forcing. The previous models and predictions primarily took into account radiative forcing and the greenhouse effect of CO₂. The increase in temperature due to radiative forcing of CO₂ gets distributed around the globe, and the effect is felt uniformly throughout the world. However, the physiological effect of CO₂ is region-specific since it differs with the vegetation of each region, and is thus heterogeneous. CO₂ physiological forcing affects other aspects of climate change too. The latent heat flux from the surface increases by about 2.85 Wm⁻² due to CO₂ radiative forcing that causes increased evaporation; whereas the physiological effect causes a decrease of latent heat flux by about 1.54 Wm⁻² due to decreased canopy transpiration, especially in the regions covered by dense forests. Relative humidity over most of the land surface changed by less than 1% due to CO₂ radiative forcing, whereas CO₂ physiological forcing caused a decrease of up to 7% in regions such as the Amazon and Central Africa, as a result of decreased canopy transpiration. CO₂ radiative forcing causes increased low-level cloudiness, increasing planetary albedo (reflectance of solar radiation away from the planet), whereas the opposite is caused due to CO₂ physiological effect.

Recognition of the important role that CO₂ physiological forcing plays may call for changes in the use of some of the familiar and commonly employed formulae and methods, such as the Clausius–Clapeyron (CC) equation that has been traditionally used in estimating the amount of saturated water vapour in the atmosphere for a given temperature. One can easily estimate changes in atmospheric water vapour caused by the greenhouse effect of CO₂ using the CC equation. It is not so simple when it comes to the CO₂ physiological effect, because the rise in temperature itself is intricately associated with decreased atmospheric water vapour due to decreased evapotranspiration. Similarly, measures such as global warming potential (GWP) need to be modified to account for the enhanced role of CO₂ in causing global warming.

The work by Cao et al. is important in other ways too. It is an example of how better models lead to better predictions. As J. Srinivasan (Indian Institute of Science, Bangalore) mentions in an interview to me: ‘Modelling vegetation is comparatively new. Before 20 years, it was mostly modelling bare land. Slowly, we have added vegetation and it is getting more and more complicated. The type of model that Bala is running, I am sure, is typically a 100 km x 100 km box. So we have to represent the vegetation that would exist in such a box, what impact it will have on radiation, moisture and so on. One of these days, we may get resolution of about 1 m. Then each 1 m x 1 m box will represent one plant.’ The paper also points to how land-use change can affect climate change. As Bala says, ‘Take a simple example of chopping trees for crops. The transpiration characteristics are going to be completely different between the two scenarios. You have huge water-vapour flux in the case of forests, and in the other case when you have grasses, you are going to have reduced transpiration. And if you construct buildings instead, you would have completely removed the transpiration. So there are a few scientific issues that should be taken into account when we talk about climate change caused by land-cover change. Apart from water-cycle changes caused by changes in transpiration, there could be changes in the carbon content over land – when you cut trees, photosynthetic removal of carbon is gone. Albedo of forests versus grasses is another aspect, since grass reflects more light than forests. This, however, is already taken into account in models like the one that we have.’

It is reasonable to believe that we are moving towards greater understanding of the intricate interactions of various components of the earth, and more comprehensive and realistic modelling of the earth. However, there is still a long way to go. For instance, Srinivasan points out: ‘The effect of CO₂ on the way the stomata behave gives a whole new dimension to the problem. CO₂ was thought to affect only radiation, but now we are saying that it is also going to affect transpiration. Locally, the effect on Amazon will be huge, and over land it has a huge impact. It is a whole new complication. Most of us have spoken only about radiative forcing, but the effect of vegetation is not fully recognized in any model of the IPCC AR4. So there will be new models coming up in AR5.

In fact, the complexity of earth system science goes beyond various factors that affect global warming alone. Increase in CO₂ concentration itself has other impacts such as increase in ocean acidity. A paper on ‘Planetary boundaries’ has listed as many as nine ‘boundaries’ that we would be likely to cross in the near future if we persisted with ‘business as usual’, including global warming, ocean acidification, ozone depletion, global freshwater use, land system change and the loss of biodiversity. The complexity in climate science even goes beyond purely scientific problems – IPCC working groups assess the impacts of climate change on socio-economic systems and evaluate possible adaptation strategies. Ambiguity in predictions, despite the care that goes into their preparation, is another issue. As Srinivasan says, ‘Earth system science is not at the same level as physics and chemistry. There is a lot more uncertainty’.

Carbones: divalent C(0) compounds

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Carbon is known to form covalent bonds and give stable tetravalent species with C(IV) oxidation state. Though several other possibilities like free radicals, carbones and carbenes are known, they are all considered to be reactive intermediates. Stabilizing these unusual states of carbon became a laboratory curiosity for several chemists during the past five decades, and efforts in this direction led to several new species like ‘stable bottlable carbones’ – N-heterocyclic carbenes (A, Figure 1), also found to be useful, offering exciting opportunities. Other examples in this class which provided immense scope for novel chemistry are triplet persistent carbenes (B)², pentacoordinate (C)³ and hexacoordinate carbon (D)⁵ system. The latest member in this group of carbon compounds are carbones (1-8, Figure 2) with C(0) oxidation state. Such carbon compounds are characterized by the presence of a central carbon atom carrying two lone pairs of electrons, i.e. none of the four electrons of carbon is involved in bond formation. This is possible because the central carbon accepts electrons from Lewis bases and is involved in the formation of the coordination (captodative) bonds; thus carbon behaves like an electron-accepting metal.

Compounds with C(0) state are known since 1961. C(0−PR₃) was obtained in a reaction of methylidebis-(triphenylphosphonium)bromide with a suspension of potassium in boiling purified diglyme. This species was considered as a carbene or allene or ylide to satisfy known chemical bonding knowledge. Such erroneous description prevented the growth

Figure 1. Novel bonding environments identified for carbon.

Figure 2. Examples of recently generated carbones, their metallic complexes and their nitrogen analogues.