One approach to identifying germ-line specific genes downstream of *tudor* is by screening for maternal-effect sterile mutations. Although such screens are difficult in *Drosophila*, they can be done[11] and could identify the germ-line signal gene or else verify that a gene that has already been identified encodes the signal. Screens for maternal-effect sterile mutations in *Caenorhabditis elegans* have identified five genes required for germ-line development[12]. Most pertinent to the issues discussed here, the *C. elegans* mutations do not disrupt germ granules and seem to affect the germ line only. Whether the differences between maternal, germ-line-required genes in flies and worms reflect differences in the types of mutations screened for, different functions of germ granules in the two species or different mechanisms of germ-line specification, are matters that remain to be determined.

Insights into germ-line development are coming not only from *Drosophila* and *C. elegans*, but also from *Xenopus*. When primordial germ cells are transferred to ectopic locations, they do not develop into germ cells but instead join other tissues and differentiate into a variety of somatic cell types[13]. This shows that *Xenopus* germ plasm, with its associated germ granules, does not irreversibly commit the cells that receive it to a germ-line fate and that the correct environment is crucial for germ-cell differentiation. Indeed, all studies in *Drosophila* in which ectopically formed germ-line precursor cells have been proven to be functional have involved transferring them to a normal location for migration to the somatic gonad[1,2].

So, whatever the germ-line signal turns out to be, it may not be a 'determinant' in the strictest sense of the word — the determination of germ-cell fate may require other environmental cues or may be easily over-ridden. Indeed, the germ signal may not instruct primordial germ cells so much as protect them from somatic differentiation signals[13]. □

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CLIMATE FEEDBACKS

An air-conditioned greenhouse

Graeme Stephens and Tony Slingo

WITH the oceans assuming an ever greater significance in our understanding of climate, there is obvious interest in the claim of Ramanathan and Collins[1] that there is a natural thermostat which prevents sea surface temperature (SST) rising above 305 K. The mechanism, which relies on extensive cirrus cloud cover put up over the warmest waters to reflect solar radiation, is challenged by Fu *et al.* on page 394 of this issue[2]. They argue from satellite data that changes in cirrus cover are related more to changes in atmospheric circulation than to SSTs, and that changes in surface evaporation are more important than Ramanathan and Collins allow. This evaporation provides continuous air conditioning of the tropical SSTs, reducing the need for any thermostat.

That Ramanathan and Collins's study should be provocative is not surprising, as the topic of climate feedbacks is highly controversial. Although it is attractive to use observations to study feedbacks, it is often impossible to separate cause and effect. With innovative use of observations obtained before and during the 1987 El Niño climate fluctuation in the Pacific, Ramanathan and Collins tried both to isolate and to quantify the cloud feedback. They propose a simple relationship between changes in sea surface temperatures, cirrus clouds and solar radiation, and assume that other processes are of secondary importance. But can cause and effect be established so clearly in the equatorial Pacific, where the conventional wisdom is that SSTs are maintained by many coupled air–sea interactions and ocean–atmosphere transport processes, operating on a variety of time and space scales[3,4]?

Several processes are known to play important roles in determining the SST distribution. In his critique of the idea, Wallace[5] articulated the common belief that evaporation increases with SST and so acts to smooth out local SST maxima. But recent studies[6] show that evaporation is not necessarily higher over warmer SSTs. Ramanathan and Collins note[7] that the climatological evaporation decreases along the equator from the east Pacific (regions of cooler SSTs) to the warm pool region where the SSTs are a maximum, contrary to what may be expected from Wallace's arguments. But this observation does not diminish the importance of evaporation, either to the heat budget of the equatorial Pacific as a whole, or to the SST anomalies that occur during El Niño. This is supported by studies of the role of transients such as the intra-seasonal oscillation and cold surges[4] and by recent model simulations of El Niño[8].

Large-scale motions also play a significant role in governing the observed distributions of cloudiness and SST. The evolution of El Niño is thought to be influenced principally by shifts in the circulation patterns of both the atmosphere and oceans[3,4,8]. This strong dynamical influence is perhaps the most fundamental difference between Ramanathan and Collins and Fu *et al.*, who support Wallace's belief that large-scale dynamical processes spread local influences to other regions of the tropics and that analyses like that of Ramanathan and Collins need to consider this larger domain. They show that the correlation between SST and cloudiness breaks down on the largest scales, which they believe are the most important. Ramanathan and Collins argue that their thermostat operates locally, over the highest SSTs, with atmospheric motions invoked to export the longwave cloud forcing from the region. This must require a selection process, as this feedback does not apply to all regions of high SST. For example, over the western Pacific during El Niño the SSTs are still near their maximum values, but there may be no deep convection or cloudiness.

Precipitation is another important process relevant to tropical SSTs. Precipitation exceeds evaporation in the west Pacific, providing an influx of fresh water into the ocean. This reduces the salinity of the upper few metres of the mixed layer, creating a stable, less-dense layer of water at the surface (the so-called fresh-water lens). This stable layer resists wind driven mixing with the colder underlying water and is heated by the absorption of solar radiation[9], thus further stabilizing the layer. Such a warmed layer promotes further convection, more rainfall and further warming. Perhaps Ramanathan and Collins's thermostat operates only over such regions of significant fresh water input. Alternative mechanisms[3,4] to constrain SSTs in these regions are the transients mentioned above and the episodic mixing events driven by westerly wind bursts that are strong enough to access the colder water below the fresh lens, thereby cooling this layer and limiting the SSTs.

The data from the satellite-based Earth Radiation Budget Experiment (ERBE), used by Ramanathan and Collins, show a remarkable and as yet unexplained near-cancellation over tropical convection between the large cooling due to the reflection of solar radiation back to space and the equally large greenhouse warming due to trapping of upwelling thermal radiation. As seen from space, the net effect of clouds is therefore close to zero, but the heating has been redistributed significantly within the column[10]. Ramanathan and Collins recognize that the cooling effect is felt at the surface, whereas the greenhouse warming occurs within the atmosphere. They claim that this warming is advected away by the atmospheric circulation and does not influence the local SSTs, which experience only the cooling effect. However, modelling studies[10,11] show that the atmospheric warming induces changes in the vertical motion field and thereby influences both the precipitation and circulation fields, which in turn influences the cloud cover at all levels.

Our understanding of the processes that maintain the warmest SSTs on the planet is rudimentary. Compared with the tropical eastern Pacific, the western Pacific is a region where the winds are generally light and the evaporative heat flux is small, where the structure of the ocean mixed layer is complex and the SST is highest and where large-scale east–west and meridional circulation of the atmosphere ensures significant moisture convergence to support the deepest convection, heaviest rainfall and smallest fluxes of solar radiation into the ocean. How these processes intimately link together is not well understood. We have attempted to expose only the simplest aspects of these coupled processes and suggest that the longwave cloud forcing, the precipitation and evaporation as well as dynamical influences on cloud cover must also be assessed to determine whether Ramanathan and Collins's thermostat can function. It is our view that it is impossible to isolate a given feedback unambiguously from other coupled processes using available observations.

Nevertheless, the thermostat and the air-conditioning mechanisms are tantalizing hypotheses which perhaps can only be tested fully by models of the coupled ocean–atmosphere system, once these models have demonstrated sufficient realism. To this end, improved basic understanding of the processes of evaporation, precipitation and radiative transfer and how they couple, together with a better understanding of the influence of large-scale atmospheric and oceanic circulation on these processes, is needed urgently. So it is most timely that a major international experiment will be conducted later this year in the west Pacific; the Tropical Oceans and Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE[12]). This will provide some of the sophisticated new observations which are needed to improve our understanding of the processes which maintain the warm sea surface of the equatorial Pacific. ☐

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ORE GEOLOGY

A little rain must fall

Andrew P. Gize

DEEP below the permafrost of northern Alaska, rainwater (meteoric water) which fell perhaps as long ago as 10^5–10^6 years over the Brooks Range mountains in the centre of the State, is carrying heat and minerals through aquifers to the northern coastal plains. In showing this, using detailed borehole studies, Deming *et al.*[1] have confirmed the geochemically and economically important roles that long-range groundwater migrations can have in large sedimentary basins. In addition, their data provide a solid framework against which many geological and geochemical concepts can be evaluated.

The significance of groundwater flow in sedimentary basins is that it provides a fundamental means of transferring heat and mass. The consequences are varied, and include control over the extent of mineral equilibrium or disequilibrium assemblages in the sediments, the force responsible for petroleum secondary migration, and control over the transport and location of some types of metalliferous ore deposits.

Several interpretations have been put forward to describe the sources and driving forces for the water. Some water could be expelled during clay mineral structural transformations or by compaction from overlying sediments[2]. Alternatively, water could be driven by meteoric water precipitated on topographically high regions, providing a hydraulic head[3], or by density gradients resulting from thermal expansion or salinity gradients which then induce free convection[4]. Each of these alternatives has merit in certain circumstances. Nevertheless, a generalized observed pattern has emerged for groundwater flow in basins bordering mountain ranges[1]. In the mountain-range foothills, new meteoric water recharge depresses the geothermal gradient and surface heat flow as it moves downwards. In the basin centre, groundwater flow tends to be horizontal, with little variation in the vertical heat flow. At the far end of the basin, the fluid flow, now rising, is controlled by details in the basin geometry, and localized highs arise in the geothermal gradients and surface heat flow.

The results of Deming *et al.* are the culmination of a 10-year collaborative programme of the US Geological Survey and the National Petroleum Reserve Alaska, covering an area of approximately 300 × 500 km^2 between the Brooks Range mountains and Prudhoe Bay on the northern coast. The borehole data were obtained between 1977 and 1984, and were used to confirm the generalized heat flow model for the basin[5]: in the Brooks Range foothills the vertical geothermal gradients are less than 22 °C km^{-1} whereas on the coastal plain they are as high as 53 °C km^{-1}. Although it was suggested then that the

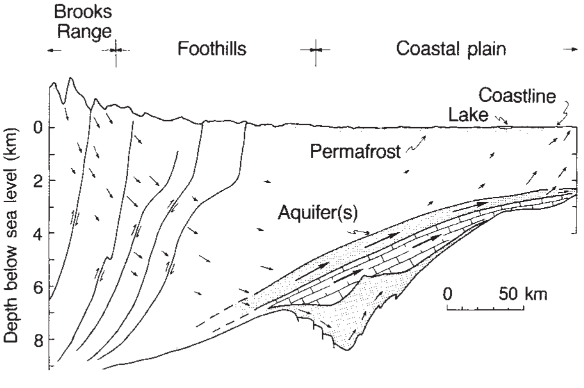

FIG. 1 Conceptual model of regional groundwater flow in the North Slope of Alaska (from ref. 1).