Reductions in stratospheric ozone and increases in GHG concentrations, which radiatively cool the low and middle stratosphere during the polar night, are obvious candidates (N. P. Gillett, University of Oxford). On shorter, seasonal time scales, an apparent delay in the wintertime tropospheric response to changes in the stratospheric circulation could lead to useful intermediate-range predictability (M. P. Baldwin, Northwest Research Associates).

The ocean may also have an appreciable influence on the atmosphere. New evidence presented at the meeting (C. Deser, National Center for Atmospheric Research) shows that the tendency of the ocean to preserve its thermal state from one winter to the next may impress some persistence on the atmosphere. A new statistical analysis revealed patterns in Atlantic sea surface temperatures (SSTs) that precede specific phases of the NAO by up to 6 months (A. Czaja, Massachusetts Institute of Technology; M. J. Rodwell, Hadley Center, UK Meteorological Office). Moreover, it has recently been shown (*4*, *5*) that atmospheric general circulation models, forced with the known global evolution of SST and sea ice cover, reproduce the observed (see the first figure) multiannual and longer term changes in the NAO. This indicates that low-frequency North Atlantic climate variability is not merely stochastic atmospheric noise but rather contains a response to changes in ocean surface temperatures and/or sea ice. Furthermore, new results (M. P. Hoerling, NOAA-CIRES Climate Diagnostics Center) link the recent NAO trend to a progressive warming of tropical SSTs, in particular, the observed warming of the tropical Indian and Pacific Ocean waters. The latter is also predicted to occur as a result of increases in GHGs.

The Chapman Conference resulted in a new, invigorated look at seasonal-to-interannual prediction beyond El Niño and a deeper understanding of anthropogenic climate change. Much remains to be learned about the NAO, but it seems increasingly less likely that natural variability is the cause of the recent NAO trend, regardless of whether the forcing is from the stratosphere, the ocean, or other processes yet to be identified.

References and Notes

1. The North Atlantic Oscillation, Ourense, Spain, 28 November to 1 December 2000. Abstracts and other information available at www.ldeo.columbia.edu/NAO/conference/chapman_conf.html. The speakers mentioned in the text are merely representative of the more than 170 papers presented at the meeting.
2. T. L. Delworth, K. W. Dixon, *J. Clim.* **13**, 3721 (2000).
3. D. W. J. Thompson *et al.*, *J. Clim.* **13**, 1018 (2000).
4. M. J. Rodwell *et al.*, *Nature* **398**, 320 (1999).
5. V. M. Mehta *et al.*, *Gephys. Res. Lett.* **27**, 121 (2000).

PERSPECTIVES: FLUID DYNAMICS

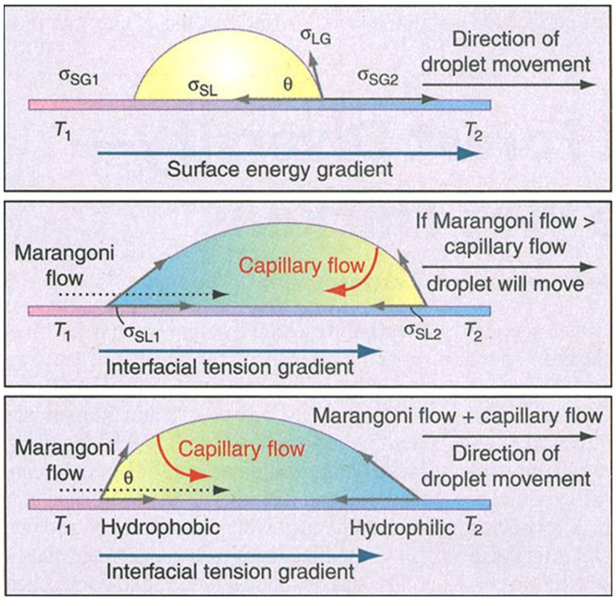
Droplets Speeding on Surfaces

Darsh T. Wasan, Alex D. Nikolov, Howard Brenner

Numerous processes from offset printing to painting depend on the rapid spreading of water droplets on solid surfaces. On page 633 of this issue, Daniel *et al.* (*1*) report on the remarkably fast movement of liquid drops on a surface with a radial temperature gradient that generates a surface tension–driven fluid motion, also known as Marangoni flow. They achieve this high-speed droplet movement through a clever manipulation of the forces acting on the droplet. The concept may be of interest for numerous industrial processes, such as coating, soldering, printing, cooling, photolithography, and microfluidic device fabrication.

Examples of flow driven by surface tension gradients abound. Consider the calming effect of oil on troubled water, the "dance" of a camphor ball on a water surface, the ripples that form in the skin of chocolate pudding near the cup center, and the tears of wine in a wine glass. Thomson (*2*) and Marangoni (*3*) were the first to investigate and begin to explain this type of flow in the mid-19th century. Variations in temperature or liquid composition cause a spatial variation in surface tension at a liquid-gas and/or solid-liquid surface, creating a tangential stress at that surface. This stress or surface traction acts on the adjoining fluid, causing interfacial fluid motion, which is in turn transmitted to the bulk fluid (*4*).

In their experiments, Daniel *et al.* (*1*) combined the Marangoni flow caused by a temperature gradient with the directional flow generated by a deliberately altered wettability of the solid surface. The wettability gradient was created by depositing hydrophobic molecules on the central part of a hydrophilic surface and then forming water drops by condensing saturated steam on the hydrophobic region. To create a temperature gradient along the solid surface, they circulated cold fluid beneath it. As the drops moved toward the cooler area of the solid surface, which was also more hydrophilic (that is, more easily wet by water), they grew by coalescing with smaller surrounding drops. High-speed video observations show that the water drops moved as fast as 1.5 m/s.



Different mechanisms of droplet flows. (Top) Droplet movement due to a surface energy gradient. Young's equation (*8*) defines the force balance between the respective interfacial tensions existing at the solid-liquid (σ_{SL}), solid-gas (σ_{SG}), and liquid-gas (σ_{LG}) interfaces and the contact angle (θ). **(Middle)** Flow patterns inside the droplet and on the liquid-solid interface due to a surface or/and interface gradient and capillary pressure. The droplet will only move if the capillary flow is exceeded by the Marangoni flow. **(Bottom)** Flow patterns inside the droplet and on the liquid-solid interface due to a surface or/and interface gradient and capillary pressure; the solid surface wettability increases in the direction of drop movement. Capillary flow drives the droplet in the same direction as Marangoni flow, leading to fast droplet movement (*1*).

To put these observations in context, let us consider three different situations in which a water drop on a solid surface with an imposed temperature gradient may find itself (see the figure). In the simplest case, it is only the surface energy of the solid surface, σ_{SG}, that drives the flow; a droplet placed on a solid surface will move in the direction of higher surface energy (to the right if $\sigma_{SG2} > \sigma_{SG1}$) (see the top panel). Things become more complex if the surface tension is not uniform throughout the droplet. The difference in surface tension (σ) along the length of the drop (L), generated by a temperature gradient, creates a Marangoni flow because the solid-liquid

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surface tension is greater at the front surface of the spreading droplet (σ_{SL2}) than at the rear (σ_{SL1}). Marangoni flow pushes the drop forward, but this flow meets resistance. As the droplet moves, the advancing contact angle exceeds the receding contact angle, causing the profile of the drop to become asymmetric (see the second panel). The curvature of the advancing meniscus is less than that of the receding meniscus. This curvature difference of the expanding drop creates a pressure difference across the drop, producing a capillary flow that opposes the Marangoni flow. The drop moves only when the surface tension gradient overcomes the capillary effect.

Daniel *et al.* present an elegant solution. Not only do they overcome capillary flow, they harness it by creating a directional flow that enhances drop movement (see the third panel). They modified the solid surface so that the droplet grown on the hotter hydrophobic portion of the surface moves under both capillary flow and surface tension gradient to the cooler hydrophilic portion of the solid surface. The curvature of the advancing meniscus becomes greater than that of the receding meniscus, and capillary pressure moves the droplet further.

Daniel *et al.*'s observations show that the droplets form and grow through the condensation of nuclei. When the surface tension gradient becomes sufficiently large, the droplets begin to move along the solid surface toward the low-temperature region where the surface tension is higher. The droplet surface stretches, and the droplet assumes a semicylindrical shape. The surface stretch produces a larger surface tension gradient, which drives the flow and accelerates the droplet motion. The moving droplet coalesces with smaller droplets formed by the condensation of steam on the solid surface. Because these droplets are at a lower temperature and thus have a larger surface tension, droplet coalescence increases the surface tension gradient along the drop surface, moving the drop faster.

A simple model can be used to estimate the maximum lateral velocity at the drop surface (V_{max}) due to the surface tension gradient. The model ignores the gravitational and capillary force contributions. The spreading droplet rate is specified by the balance between the shear forces at the gas-liquid surface and the tractive forces due to the surface tension gradient (*5*, *6*):

$$V_{max} \approx (h/2\mu)\, d\sigma/dL$$

where h is the thickness of the spreading droplet, μ is the viscosity of the droplet liquid, and $d\sigma$ is the surface tension change along the drop length dL. Consider a water droplet with a diameter of 0.2 cm (corresponding to a droplet thickness of 0.1 cm) with a contact angle of 90°, viscosity of 10^{-2} g cm^{-1} s^{-1}, and surface tension gradient of $d\sigma/dL$ = 10 dyne cm^{-2} (*7*). Using the equation above, we find that the droplet can move with a speed of 50 cm/s under the surface tension gradient alone. The additional capillary flow (which is proportional to σ/R, where R is the local drop curvature radius) can easily intensify the droplet movement so as to achieve speeds of more than a meter per second, as observed by Daniel *et al.*

The demonstration that capillary flow can aid the Marangoni flow to accelerate the wetting and spreading of liquids over surfaces is not only intriguing but holds great promise for practical applications. The underlying phenomena—droplet formation by nuclei condensation, growth by coalescing with other drops, and subsequent movement under the combined action of temperature and wettability gradients—are, however, quite complex. They must be better understood before the promise of this novel concept can be fully realized.

References
1. S. Daniel, M. K. Chaudhury, J. C. Chen, *Science* **291**, 633 (2001).
2. J. Thomson, *Philos. Mag. Ser. 4* **10**, 330 (1855) [summarized in J. C. Maxwell's article on "Capillary Action," *Encyclopedia Britannica* (Samuel L. Hall, New York, ed. 9, 1878)].
3. C. Marangoni, *Nuovo Cimento Ser. 2* **5/6**, 239 (1872).
4. D. A. Edwards, H. Brenner, D. T. Wasan, *Interfacial Transport Processes and Rheology* (Butterworth-Heinemann, Boston, MA, 1991), pp. 161–185.
5. B. Levich, V. Krylov, *Annu. Rev. Fluid Mech.* **1**, 239 (1969).
6. P. G. De Gennes, *Rev. Mod. Phys.* **57**, 827 (1985).
7. The value for the surface tension gradient is based on the surface tension difference of water between 20°C (σ =72.7 dyne/cm) and 80°C (σ = 62.6 dyne/cm).
8. T. Young, *Philos. Trans. R. Soc. London* **95**, 65 (1805).

PERSPECTIVES: ECOLOGY

Tropical Forest Diversity—The Plot Thickens

David F. R. P. Burslem, Nancy C. Garwood, Sean C. Thomas

The tropical forests of the world support a huge number of tree species—more tree species are found in 0.5 km^2 of some tropical forests than in all of North America or Europe. Although tropical ecologists have put forward a number of hypotheses to explain this species diversity, testing these hypotheses has been hampered by the lack of field studies with sufficiently large long-term data sets.

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To fill this void, the Center for Tropical Forest Science (CTFS) of the Smithsonian Tropical Research Institute has formed a network of permanent forest sites in the tropics—the forest dynamics plot (FDP) network—that are between 15 and 52 ha in size (see the figure, next page) (*1*). By counting, identifying, and measuring all trees greater than 1 cm in diameter in the FDP sites at 5-year intervals—with a standardized protocol (*2*) to facilitate comparisons between sites—CTFS has obtained a unique and comprehensive data set. This data set provides valuable insight into the distribution, abundance, and dynamics of tropical tree species. The physical, demographic, and taxonomic information accumulated for each site has also catalyzed research on, for example, the dynamics of soil seed banks (*3*), photosynthesis (*4*), the economics of nontimber forest products (*5*), and molecular analyses of gene flow within tree populations (*6*).

Two decades' worth of results from the 16 FDP sites were discussed at a workshop on tropical forest diversity in Singapore (*7*). One goal of the workshop was to determine from the FDP data sets the factors that are most crucial for maintaining species diversity in tropical forests. Factors that are thought to be important for species coexistence include: habitat disturbance (different regeneration requirements); natural enemies (different susceptibilities to pests, predators, and pathogens); limitations on seed dispersal; variation in nutrient availability; niche differentiation (different requirements for limiting resources); competitive equivalence (inability of a species to outcompete similar species); and fluctuating recruitment (which, together with juvenile persistence, may result in a species "storage effect"). Hubbell (USA) (*8*) concluded that evidence from the FDP sites supports the contribution of at least four factors—niche differentiation, natural enemies, seed dispersal limitation, and competitive equivalence—to the maintenance of tropical forest diversity. Data did not show, however, that habitat disturbance or fluctuating recruitment were important factors.

Although debate continues, the FDP data suggest that no single factor is likely to be sufficient to account for tropical tree diversity. The historical polarization of this debate into camps favoring different

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