Dishing Up
Wave-Mean Flow Interactions

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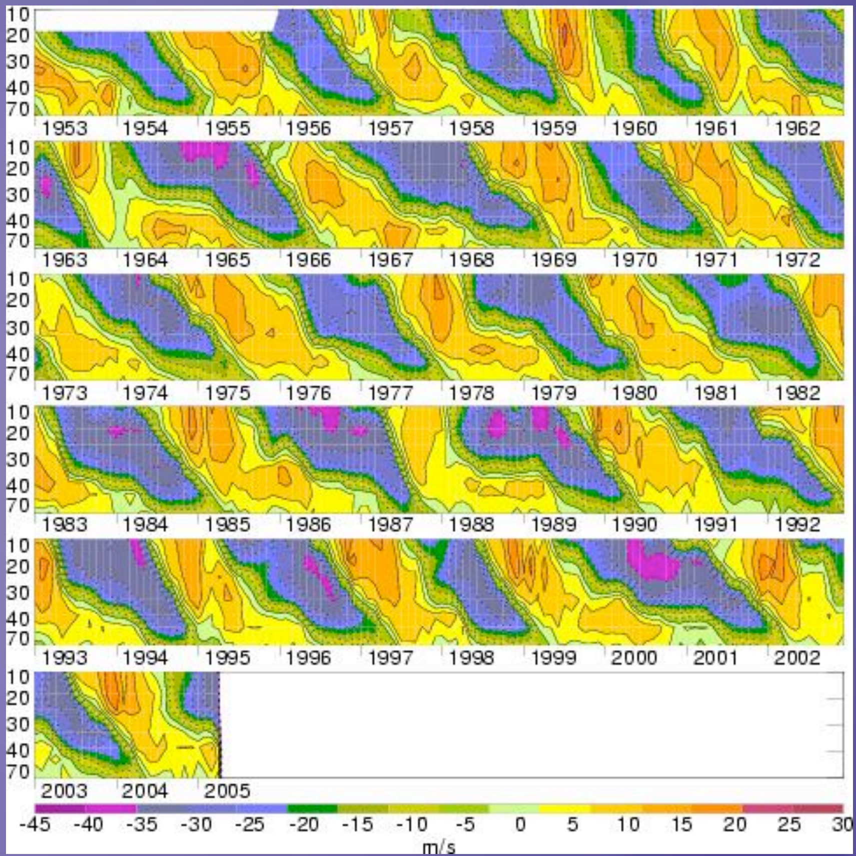
Setting the stage for this talk

- **Primarily pedagogical**, anticipating some of tomorrow's talks
- Addressing common problem: divide between the research and education literatures
  - GFD research: *J. Fluid Mech*., *J. Atmos. Sci*., etc.
  - Education research: *BAMS*, *J. Geosci. Ed*., *Amer. J. Physics*, etc.
  - Very different audiences!
  - **Especially hard to find venue for pedagogy on dynamics** (too advanced for education readers, not research-y enough for research journals)
- Subject of this talk: **rescuing, examining and promulgating a good teaching idea from a nearly 20-year-old *J. Fluid Mech*. article**

This talk's topic

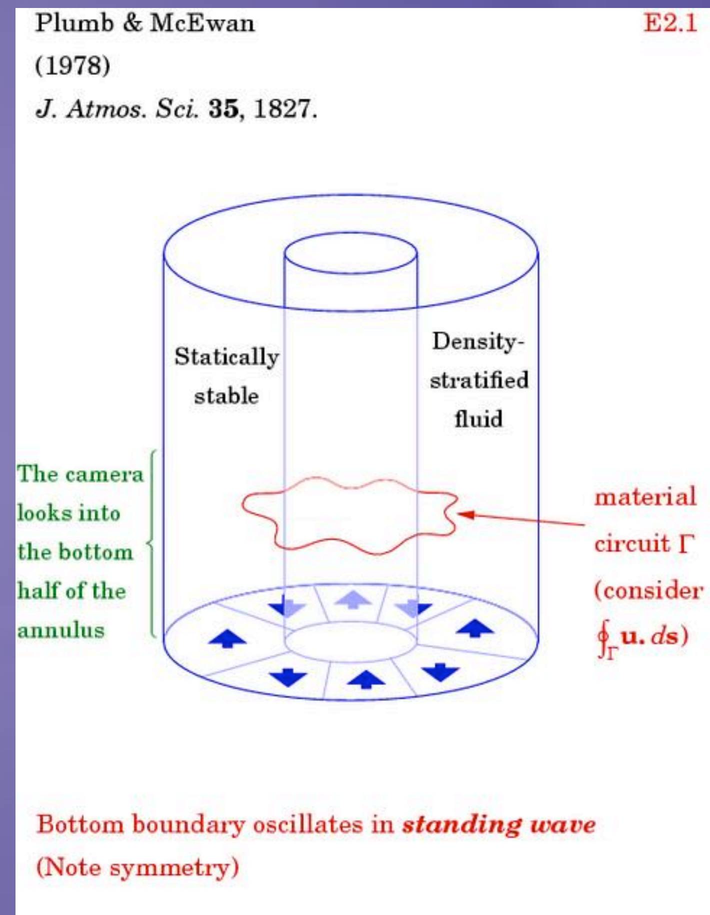
- **Wave-mean flow interactions**
  - Essential topic of geophysical fluid dynamics
  - Concept: dissipation of waves transmits energy to mean flow, causing acceleration/deceleration of mean flow toward phase speed of waves
  - Examples:
    - Longshore ocean currents
    - Stratospheric sudden warmings (Rossby waves)
    - **Quasi-biennial oscillation** (**QBO**; primarily equatorial gravity waves)



The QBO in zonal 10-70 mb winds at Singapore for 1953-2005 (blue = easterlies, yellow = westerlies)

A brief illustrative digression on the QBO, and a famous tank experiment

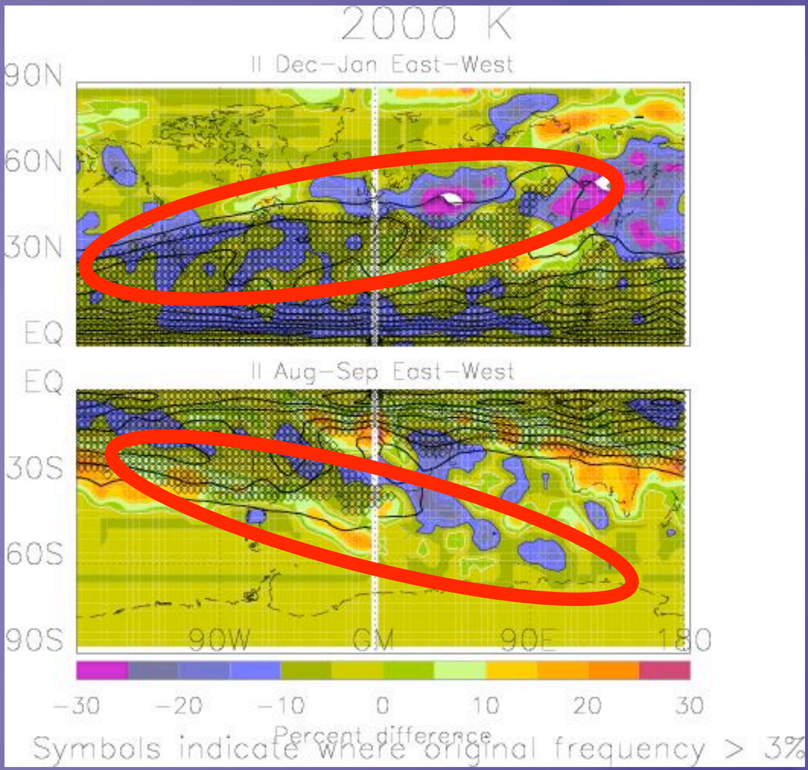
• **Plumb and McEwan** 1978 *J. Atmos. Sci.:* non-rotating tank experiment demonstrating QBO mechanism
• Oscillating lower boundary forces two waves of opposite phase speed
• Result: descending patterns of alternating-direction mean flow



http://www.damtp.cam.ac.uk/user/mem/papers/ECMWF/

The famous Plumb-McEwan tank experiment, cont.

- Original explanation: viscous dissipation of waves, causing mean-flow interaction
- **Wedi and Smolarkiewicz** 2006 *J. Atmos. Sci.*: numerical simulation of Plumb/McEwan experiment demonstrates role of wave-wave interactions and critical layers
- **Bottom line: wave-mean flow interaction explains equatorial enigmas** (equatorial superrotation, even **equatorial stratopause instability patterns** at right)



Percent difference in midwinter stratopause inertial instability frequency in QBO easterly versus QBO westerly years in a 12-year UKMO climatology. Blues: less activity during QBO easterlies vs. westerlies (work with V. L. Harvey)

But...

- **Plumb-McEwan experiment exceeds limits**
  - My experimental “prowess”
  - My undergraduates’ backgrounds
- **Need simpler “front-end” experiment** to motivate these more advanced concepts and experiments

McIntyre and Norton's "kitchen sink" experiment

- "Dissipative wave-mean interactions and the transport of vorticity or potential vorticity," *J. Fluid Mech*., 1990, vol. 212, 403-435.
- **Basic idea:** agitate an anisotropic **wavemaker in a transparent "oven dish"** on an overhead projector to create waves that drive a mean flow in a previously stationary fluid
- Voilà, **wave-mean flow interactions anyone can do and understand**

McIntyre and Norton's "kitchen sink" experiment

406 *M. E. McIntyre and W. A. Norton*

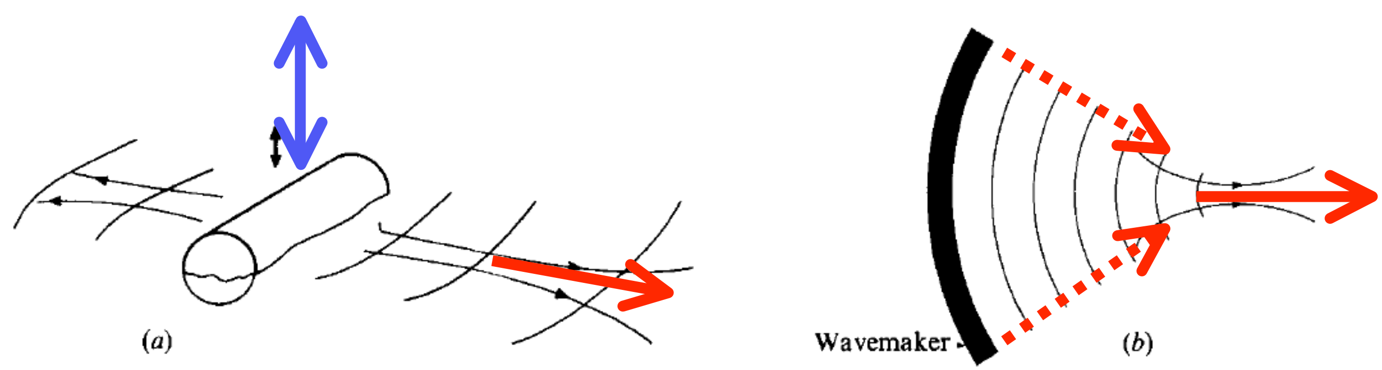


FIGURE 1. Simple lecture or laboratory demonstrations illustrating the typical nature and robustness of classical mean-flow generation by dissipating waves. (*a*) An example using water waves that requires no special apparatus. The cylinder, or any other anisotropic wavemaker, is oscillated fairly rapidly ($\gtrsim 5$ Hz) so as to radiate short waves more strongly in some directions than in others. The resulting mean streaming can be made visible (and wave dissipation enhanced) by sprinkling a little powder such as ordinary household flour on to the surface of the water. Making the cylinder oscillate vertically demonstrates that the observed mean flow is predominantly wave-induced, and not boundary-layer streaming from the surface of the wavemaker, which has the opposite sense. (*b*) By using a longer curved wavemaker in a larger tank one can focus the waves on a spot well away from the wavemaker and thus induce an easily observable mean flow concentrated near that location. Carefully stopping the wavemaker and observing the persistence of the mean flow, in either case, demonstrates that the mean flow is not merely a 'Stokes drift'. Relevant theoretical discussions are those of Longuet-Higgins (1953) and Craik (1982*a*), among others.

McIntyre and Norton’s “kitchen sink” experiment

- Modified slightly in later McIntyre publications…

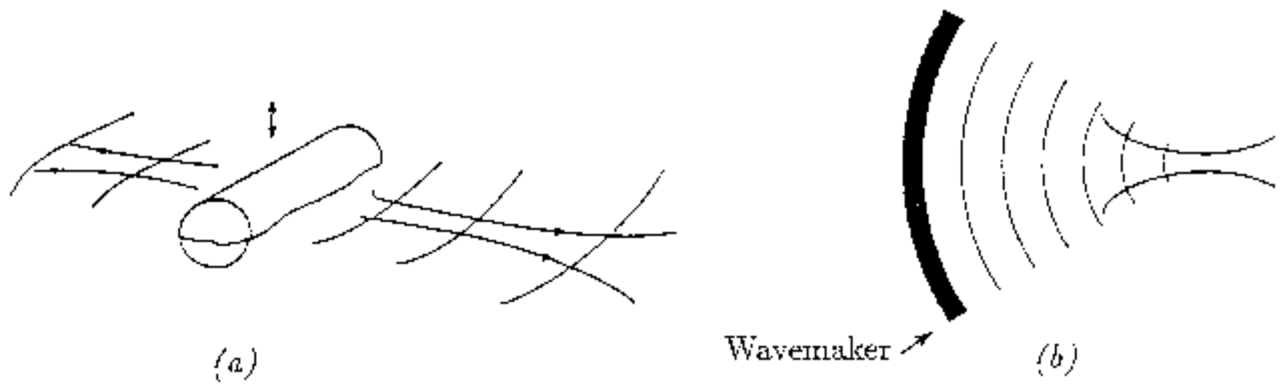


Fig. 1. Simple experiments with 5 Hz water waves, illustrating the irreversible wave-induced momentum transport that accompanies the generation of waves in one place and their dissipation in another. The strong mean flows thereby generated can be made conspicuous by sprinkling a little powder such as chalk dust on the surface of the water. Configuration (*a*) works well with a cylindrical wavemaker whose diameter is of the order of 2 to 4 cm, and can be demonstrated in a transparent dish on an overhead projector. Configuration (*b*) works well with a larger wavemaker whose radius of curvature is of the order of half a metre. From McIntyre and Norton (1990) and McIntyre (1992,3); *q.v.* for further discussion.

http://atm-www.damtp.cam.ac.uk/people/mem/oldftp/qbosolar-fig1n.gif

My modifications to the “kitchen sink”

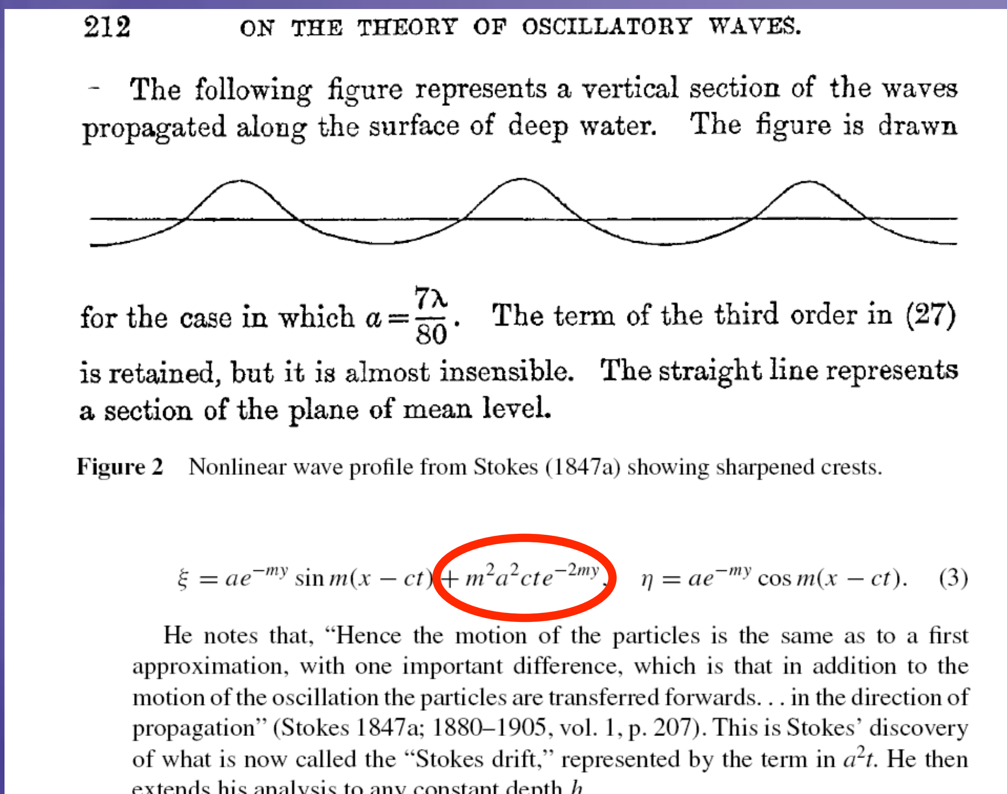
- Chalk dust better for overhead than for naked eye
  - Gives fine-grained “PV”- or “water vapor”-type view
  - Less discernible away from overhead
- Substitute/add **spices** (mixed Italian spices)
  - Cheap, handy, more visible, add dissipation
  - Sinking particles allow sense of flow at bottom
- **Cheese slicer** (sans wire) makes excellent cylindrical wavemaker, with built-in handle
- For curved wavemaker: **cut plastic cup or pie cover along chord** (about 1/4th of circumference)
- **Don’t use larger tank for curved wavemaker**
  - Instead, **force waves toward the “short side”**
  - Seems to reduce side boundary effects
  - Provides same insights without need for larger tank

The “kitchen sink” experiment:
my results with cylindrical wavemaker

The "kitchen sink" experiment: my results with curved wavemaker

Science question re: experiment

- Is it “merely Stokes drift” or wave-mean interaction?
- **Stokes drift** (1847): For waves of amplitude *a*, $O(a^2)$ displacement in direction of wave propagation



212 ON THE THEORY OF OSCILLATORY WAVES.

The following figure represents a vertical section of the waves propagated along the surface of deep water. The figure is drawn

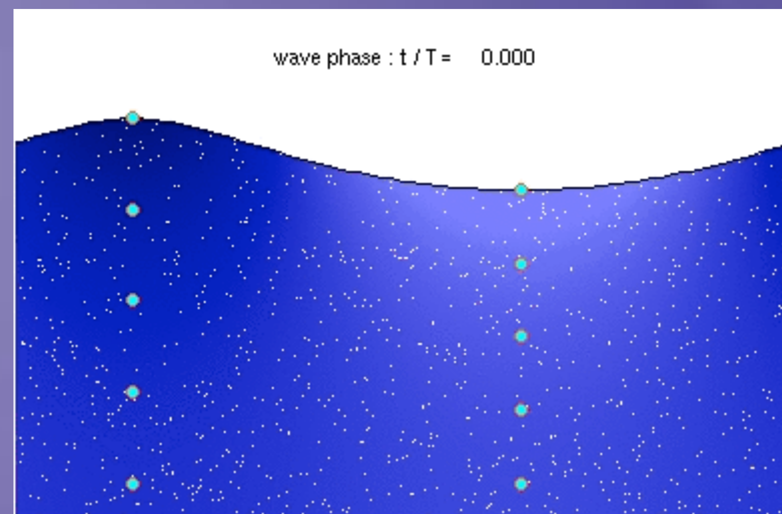
for the case in which $a = \frac{7\lambda}{80}$. The term of the third order in (27) is retained, but it is almost insensible. The straight line represents a section of the plane of mean level.

Figure 2 Nonlinear wave profile from Stokes (1847a) showing sharpened crests.

$$\xi = ae^{-my}\sin m(x - ct) + m^2a^2cte^{-2my}, \quad \eta = ae^{-my}\cos m(x - ct). \quad (3)$$

He notes that, “Hence the motion of the particles is the same as to a first approximation, with one important difference, which is that in addition to the motion of the oscillation the particles are transferred forwards. . . in the direction of propagation” (Stokes 1847a; 1880–1905, vol. 1, p. 207). This is Stokes’ discovery of what is now called the “Stokes drift,” represented by the term in a^2t. He then extends his analysis to any constant depth h.

From Craik, 2005 Annu. Rev. Fluid Mech.



http://en.wikipedia.org/wiki/Image:Deep_water_wave_after_three_periods.gif

Science question re: experiment

- **McIntyre's explanation in terms of wave-mean flow interaction seems plausible**:
  - **It's due to wave dissipation**
    - Waves disappear
    - Mean flow develops nearly simultaneously in direction of wave propagation
    - In curved wavemaker case, mean flow most pronounced where waves are focused
  - **It's *not* due to Stokes drift**
    - Stokes drift dependent on presence of waves
    - Mean flow persists long after wavemaking ceases (if a =0, term is zero even for large t)

Pedagogical application

- **Lab assignment in my GFD course at UGA:**
  - **Dish experiments**
    - Straight wavemaker; concave wavemaker; convex wavemaker, too
    - Series of essay questions
  - **Qualitative and quantitative application of concepts to middle atmosphere dynamics**
    - Application of concepts to QBO
    - For two different cases of mean flow (one westerly, one easterly), mean flow acceleration/deceleration estimated due to different equatorial waves with differing phase speeds
    - Discussion of simple gravity wave drag parameterization in terms of wave-mean flow interactions

Conclusions

- **McIntyre's "kitchen sink" experiment** is a highly useful, nearly foolproof pedagogical tool for motivating the concept of wave-mean flow interactions
- It can be performed fairly successfully with even less equipment than described by McIntyre—truly straight out of the "kitchen"
- The results are broadly applicable to a wide range of geophysical wave-mean flow interactions
- Therefore, it **seems to be an ideal "front-end" experiment to motivate understanding of other, more sophisticated experiments in fluid flow**