Prime Prime Bar: Forty Years of Fluxes

Thanks to Grant Firl

THE VERTICAL DISTRIBUTION OF PHYTOPLANKTON IN A STRATIFIED LAKE

A Thesis

Presented in Partial Fulfillment of the Requirements
for the Degree Master of Science

by

David Allan Randall

The Ohio State University
1971

Approved by

Ting Y. Li
Advisor
Department of Aeronautical
and Astronautical Engineering


Fluxes in lakes

Parameterization of the Planetary Boundary Layer for Use in General Circulation Models[1]

JAMES W. DEARDORFF—*National Center for Atmospheric Research,[2] Boulder, Colo.*

ABSTRACT—The surface stress and fluxes of heat and moisture are parameterized for use in numerical models of the general circulation of the atmosphere. The parameterization is designed to be consistent with recent advances in knowledge of both the planetary boundary layer and the surface layer. A key quantity throughout is the height, h, of the planetary boundary layer, which appears in the governing stability parameter, a bulk Richardson number. With upward heat flux, a time-dependent prediction equation is proposed for h that incorporates penetrative convection and vertical motion. Under stable conditions, h is assumed to depart from the neutral value and to become nearly proportional to the Monin-Obukhov length.

The roughness length, z_0, is incorporated in the combination h/z_0, and the parameterization is consistent with h/z_0 affecting only the wind component in the direction of the surface velocity. The direction of the surface wind and stress is derived in a manner consistent with the known value of the surface pressure gradient and theoretical studies of the decrease of stress with height.

The parameterization has been tested numerically and appears to be efficient enough to use in existing general circulation models.

1. INTRODUCTION

The planetary boundary layer (PBL) is the region adjacent to the earth's surface where small-scale turbulence is induced by wind shear and/or thermal convection and occurs almost continuously in space and time. It includes in its lowermost portion the Prandtl or surface layer, where the vertical fluxes of heat, momentum, and moisture have nearly the same magnitudes as they do at the surface itself. By contrast with the PBL, turbulence on the sub-synoptic scale occurs only intermittently in the rest of the troposphere. Above the PBL, the mechanisms which cause turbulent transport are towering cumulus clouds, clear-air turbulence associated with internal wind shear layers, and effects of topography on a scale large enough to cause upward propagation of energy through the PBL.

A general circulation model (GCM) of the earth's atmosphere should treat the PBL in a physically realistic way to relate the turbulent fluxes at the surface to the calculated variables from the GCM. Two approaches seem possible. One is to place several layers (perhaps five or six) within the lowest 2–3 km above the surface to resolve the vertical structure of the PBL crudely but explicitly. Even in this case, however, the associated vertical transports of heat, momentum, and moisture should be parameterized in a manner consistent with the existence of a PBL within the layers.

The second approach is to parameterize all aspects of the PBL in a GCM that has such poor vertical resolution that the top of the PBL may sometimes not even reach the level of the lowest interior gridpoints. The first approach may be preferable but is usually not feasible, especially with the ever present desire to increase the horizontal resolution of any model. The second approach has not been seriously attempted mainly because of lack of knowledge about properties of the PBL. However, this knowledge is beginning to accumulate, as may be seen from recent studies by Csanady (1967), Blackadar and Tennekes (1968), Gill (1968), Deardorff (1970*a*, 1970*b*), Clarke (1970*a*, 1970*b*), Tennekes (1970), Lenschow (1970), Lettau and Dabberdt (1970), and others. It therefore seems appropriate to attempt a parameterization of the properties of the PBL at this time, using the second approach. The symbols used are identified in table 1.

The basic procedure to be followed here involves splitting the problem into four parts:

1. Use the existing height, h, of the top of the PBL above sea level and values at the lowest one or two grid levels of the GCM to obtain estimates of the vertically averaged mean values of wind velocity, potential temperature, and specific humidity within the PBL.

2. Estimate the surface fluxes of momentum, heat, and moisture using a bulk Richardson number based upon differences between mean values obtained above in step 1 and the surface values. This estimate makes use of our knowledge of both the surface layer and the entire PBL.

3. Estimate the direction of the surface-level velocity using the known value of the horizontal pressure gradient at the surface. This step makes use of PBL theory and the results of step 2 and is necessary so that the direction of the surface stress can be known. The mean wind speed occuring in the bulk Richardson number can then be refined to become the component in the direction of the surface wind and steps 2 and 3 can be repeated if necessary.

[1] The research reported in this paper was done mainly at the University of California, Los Angeles, and supported in part by National Science Foundation Grant No. GA-22756.

[2] Sponsored by the Nationa lScience Foundation

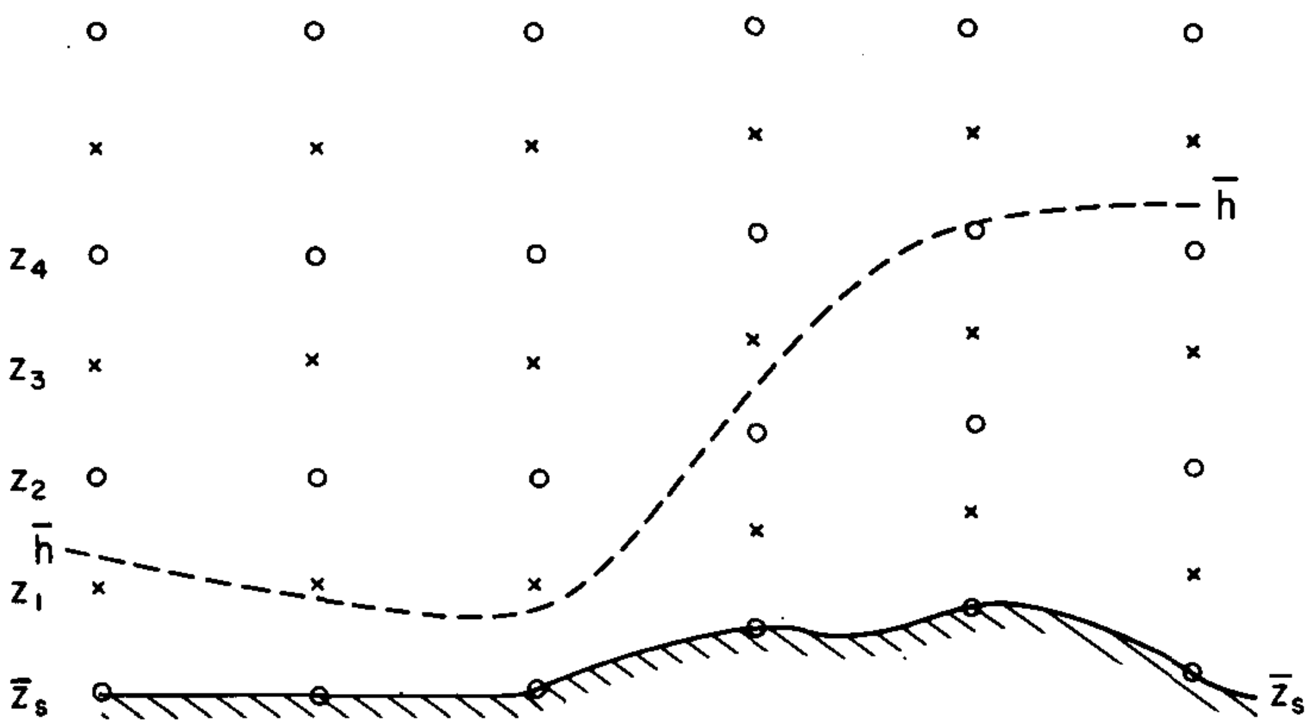


FIGURE 1.—Schematic representation of the surface, $\bar{z}_s$, the height, $\bar{h}$, of the planetary boundary layer, and GCM grid levels, $z_1, \ldots, z_4$. The *x*s denote grid points at which U, V, θ, and q are calculated; the *o*s denote points where W is calculated.

551.511 : 551.576.11

Models of cloud-topped mixed layers under a strong inversion

By D. K. LILLY
National Center for Atmospheric Research, Boulder, Colorado

(Manuscript received 3 July 1967; in revised form 29 January 1968)

SUMMARY

Theoretical models are constructed with the aim of relating, explaining and predicting features of a radiatively active turbulent cloud layer over the sea and under a strong subsidence inversion. Both dry aerosol clouds (no phase change) and wet clouds (with a phase change and latent heat exchanges) are considered. For the wet cloud case an important element of the theory is the requirement that the wet-bulb potential temperature must increase upwards in the inversion. For both cases entrainment of the upper warm air is hypothesized to lie between upper and lower limits determined from the turbulent energy budget. The dry cloud case is solved for both steady state and transient results, with only the transient behaviour depending on the entrainment hypothesis. Only steady state solutions are presented for the more complex wet cloud case and these differ somewhat for the maximum and minimum entrainment limits. Observational data from Oakland, California are used for comparison with those steady state solutions, with results indicating the essential validity of the approach. Detailed comparisons, especially for determination of the most correct entrainment rate, are hampered both by inadequate measurement of the inversion properties and by uncertainties in the net radiation flux leaving the cloud top. Computations of the latter suggest that several presently used radiation models are still in serious disagreement, at least for application to downward flux under an inversion. It is suggested that the present theory provides a partial explanation of the origin of the trade wind inversion.

1. Physical framework and motivation

A shallow turbulent moist stratum is characteristic of Equatorward flow just above the middle-latitude and tropical oceans, especially at the eastern ends of sub-tropical high pressure areas of the eastern North and South Pacific and South Atlantic oceans. This moist stratum, or marine layer, is typified by a solid or broken cloud cover, topped by a strong temperature inversion with warm dry air aloft. The extreme sharpness of the inversion, observed strikingly in kite soundings from the Meteor expedition (von Ficker 1936, examples presented by Riehl 1954), is normally partly concealed by the instrumental lag in balloon-borne radiosondes. It has often been revealed further, however, by instrumented airplane flights (James 1959; Edinger 1963, 1966) and slow-ascent radiosondes (Williams and De Mandel 1966).

Qualitative explanations for this régime, offered for many years (Petterssen 1938; Riehl 1954, Chapter 2; Neiburger 1944), were based on the following arguments. In conditions of strong or moderate subsidence the potential temperature of the lower troposphere may be substantially higher than that of the ocean surface. Since the ocean has effectively an almost infinite heat capacity, a temperature inversion or stable layer must form somewhere. The turbulence generated by surface shear could be expected to mix the lower layer and maintain a sharp, somewhat elevated inversion, while radiation from the top of a cloud would exert an additional cooling effect in the mixed layer.

In recent years the effect of stratification on the surface boundary layer has been clarified somewhat by observation and theoretical analysis. In particular, the length scale introduced by Monin and Obukhov is shown to act as an upper bound on the influence of surface shear-generated turbulence. Since this scale is not often greater than a few tens of meters, it seems that we must deny the importance of surface shear in the maintenance of a mixed layer 500 to 1,000 meters or more in thickness.

In the present theory we therefore disregard the effects of the surface shear-generated turbulence but consider radiation off the cloud tops as an essential element. In this respect we follow Petterssen, who particularly emphasized the radiative heat loss. This theory may not be valid for the occasionally observed cases of extremely shallow (< 100 m)

marine layers without condensation, but is intended to hold for the fog-, stratus- or stratocumulus-containing layer typically observed near the coast of California in the summer, and near northern Chile, southern Peru and South West Africa most of the year.

A further essential foundation of the present theory is the stability of the cloud top against penetration by the very dry upper air mass. If a parcel of the upper air is introduced into the cloud layer and mixed by turbulence, evaporation of cloud droplets into the dry parcel will reduce its temperature. If the mixed parcel reaches saturation at a colder temperature than that of the cloud top it will be negatively buoyant and can then penetrate freely into the cloud mass. In such a case the evaporation and penetration process will occur spontaneously and increase unstably until the cloud is evaporated. The condition for no change in temperature upon evaporative mixing is that the wet-bulb potential temperatures of the wet and dry layers be equal. We assume, therefore, that for stability of a cloud layer the inversion at its top must be sufficiently strong that the wet-bulb potential temperature remains constant or increases upward at the cloud top. For a difference of 5-10 g/kg in mixing ratio between mixed layer and upper dry layer this requires $\sim$ 13-26°C increase in potential temperature across the inversion. Such inversion strengths are commonly observed in west coast soundings and it appears, on the basis of somewhat inadequate data, that the theoretical requirement is usually satisfied.

We further assume that the large-scale vertical motion and the upper air (above the inversion) temperature and humidity structure are known, as well as the near-surface wind, surface temperature, and (saturated) surface humidity. Certain simplified formulations are used for calculating surface heat and moisture fluxes and radiative heat-flux. Precipitation is neglected, which probably restricts the application to rather thin and not too cold cloud layers.

The interaction of large-scale atmospheric properties and thermal convection is a principal unsolved problem in the development of forecast and/or general circulation models. The phenomenon considered here represents one form, in some respects a relatively simple one, of this interaction. There is a considerable lack of highly definitive observational data on layered convection, in fact on most kinds of non-violent cloud convection. A principal motivation for this work was to sharpen the questions to be asked and to help avoid purely exploratory observations, which may already exist in sufficient abundance.

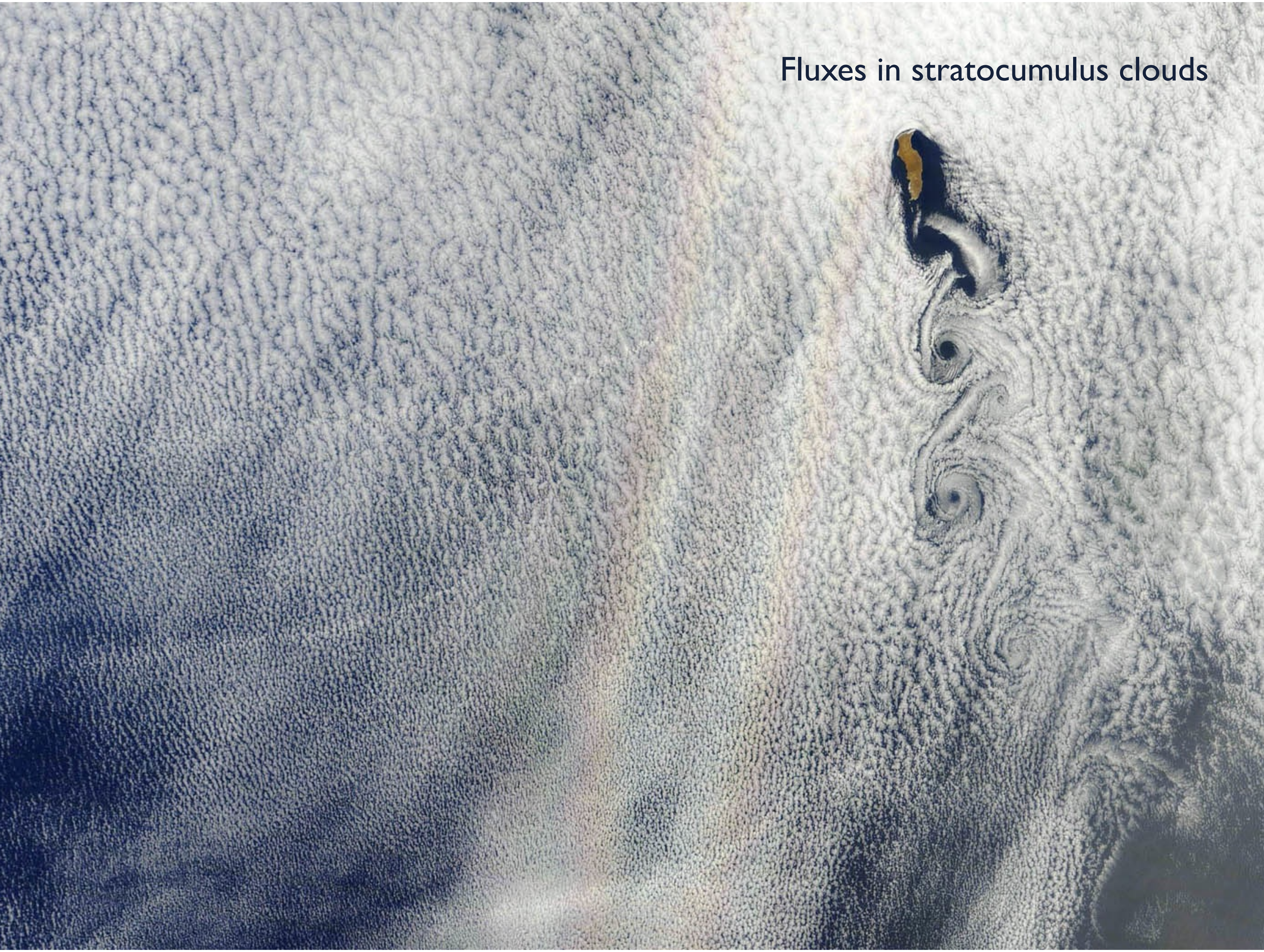
2. A simplified dry 'cloud' layer

As a simplified illustration of the mechanism which will be explored more realistically in the next section, we consider a shallow radiation-absorbing cloud of dust, smoke, or other inert matter occupying the lower part of a horizontally homogeneous air mass subject to a specified large-scale vertical motion field $w(z) \leqslant 0$. Radiative cooling is occurring in the air above the cloud at a rate which will maintain a stable potential temperature profile $\theta_U(z)$, i.e., $\partial\theta_U/\partial z > 0$. The upper layer above the cloud is assumed to be non-turbulent. The lower boundary, the Earth's surface, is maintained at a potential temperature θ_S. Turbulent heat-flux from the surface is assumed proportional to the near-surface wind and to the surface-air temperature difference through a heat transfer coefficient C_T, that is

$$(\overline{w'\theta'})_0 = C_T V_0 (\theta_S - \theta_0), \qquad (1)$$

where θ_0 is the potential temperature of the air at a small height above the surface. If this heat transfer is positive it is assumed that the entire cloud layer, from the surface to $z = H$, is well mixed at a very high Rayleigh number, and is therefore nearly isentropic with potential temperature θ_0 except very close to the boundaries. At the top of the cloud layer a net outward radiative heat flux F_{UH} tends to cool the top, and therefore the entire cloud layer.

We now proceed to derive expressions for the time rates of change of θ_0 and H, as functions of their initial conditions and the values of w, F_{UH} and θ_U, considered as


Fluxes in stratocumulus clouds

UNIVERSITY OF CALIFORNIA

Los Angeles

The Interaction of the Planetary Boundary Layer with Large-Scale Circulations

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Atmospheric Sciences

by

David Allan Randall

The dissertation of David Allan Randall is approved.

Friedrich H. Busse

Chung-yen Liu

Morton G. Wurtele

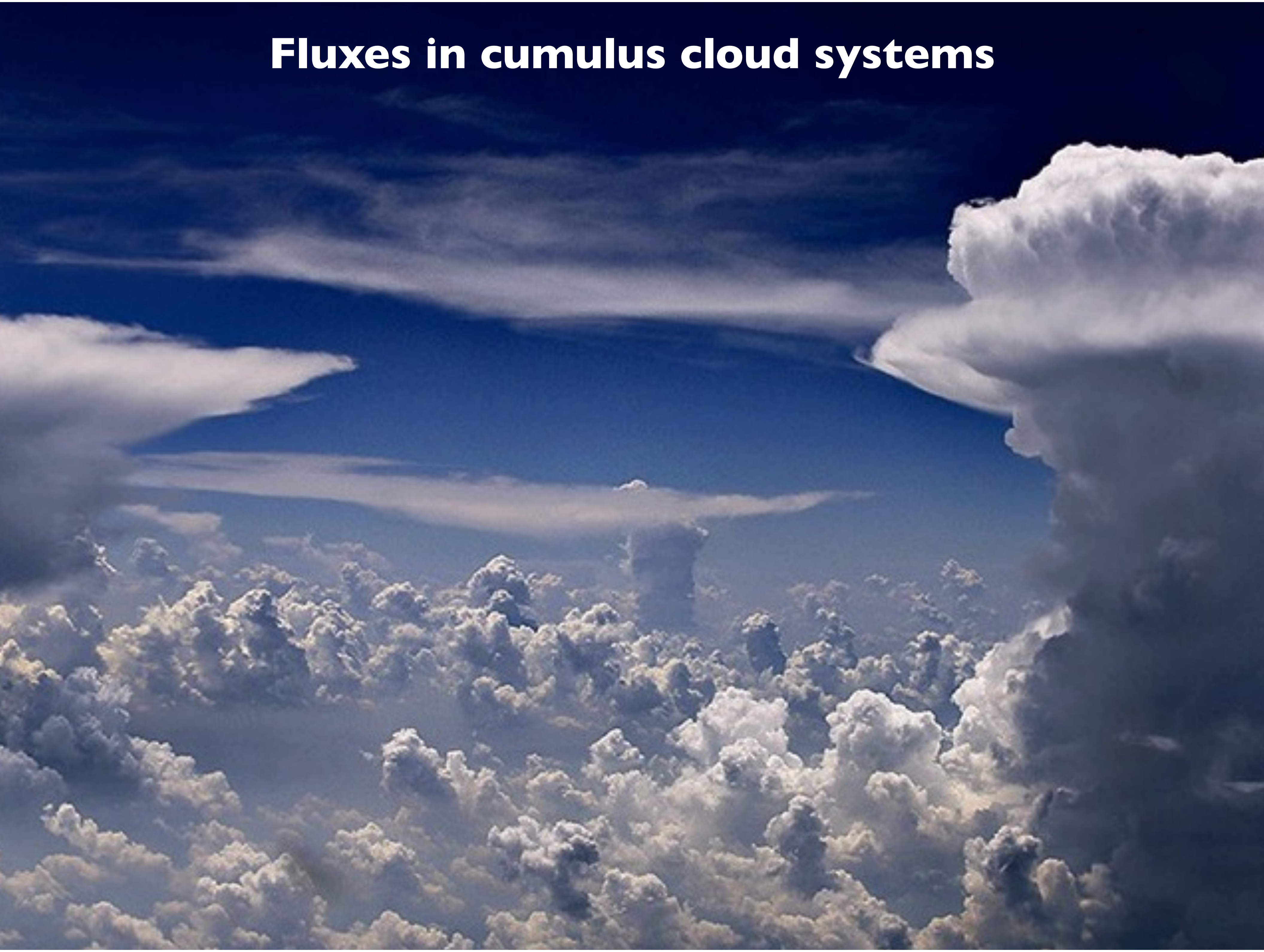
Michio Yanai

Akio Arakawa, Chairman

University of California, Los Angeles

1976

Fluxes in cumulus cloud systems



A way to talk about fluxes

- A bar means a grid-area average, also called a "*first moment*." It is a statistic. $\overline{q}$
- A prime means a departure from a grid-area average. The average of a prime is zero. q'
- A "prime prime bar," which can be called a "*second moment*," is a statistic that arises from correlated variations on unresolved scales. $\overline{w'q'}$
- Some second moments are fluxes of first moments.
- A *third moment* has the form "prime prime prime bar." Some third moments are fluxes of second moments. $\overline{w'w'q'}$
- A model that predicts anything higher than first moments is called a "*higher-order closure*" model.

HOC

HOC started in the 1960s

- Obscure technical reports
- Engineering applications
- Immediate interest from atmospheric scientists

I first learned about HOC while studying aero engineering at Ohio State.

HOC

$$\frac{\partial}{\partial t}\left(\rho_0\bar{\theta}\right)+\frac{\partial}{\partial x_j}\left(\rho_0\bar{u}_j\bar{\theta}+\rho_0\overline{u_j'\theta'}+\bar{H}_j\right)=\frac{\theta_0}{c_pT_0}\bar{Q}$$

$$\frac{\partial}{\partial t}\left(\rho_0\overline{u_i'\theta'}\right)+\frac{\partial}{\partial x_j}\left(\bar{u}_j\rho_0\overline{u_i'\theta'}+\overline{u_j'\rho_0u_i'\theta'}\right)$$

$$=-\rho_0\overline{u_i'u_j'}\frac{\partial\bar{\theta}}{\partial x_j}-\rho_0\overline{u_j'\theta'}\frac{\partial\bar{u}_i}{\partial x_j}+2\varepsilon_{i,j,k}\rho_0\overline{u_j'\theta'}\Omega_k$$

$$-\overline{\rho_0\theta'\frac{\partial}{\partial x_i}\left(\frac{\delta p'}{\rho_0}\right)}+\rho_0\frac{\overline{(\theta')^2}}{\theta_0}g_i+\theta'\frac{\overline{\partial\Im_{i,j}'}}{\partial x_j}+\frac{\theta_0}{T_0}\frac{\overline{u_i'Q'}}{c_p}-\overline{u_i'\frac{\partial H_j'}{\partial x_j}}$$

$$\frac{\partial}{\partial t}\overline{\theta'\theta'\theta'}+\bar{u}_j\frac{\partial}{\partial x_j}\overline{\theta'\theta'\theta'}+3\overline{\theta'\theta'u_j'}\frac{\partial\bar{\theta}}{\partial x_j}+\frac{1}{\rho_0}\frac{\partial}{\partial x_j}\left(\rho_0\overline{u_j'\theta'\theta'\theta'}\right)=\frac{3}{\rho_0}\overline{\theta'\theta'\frac{\partial H_{3,j}'}{\partial x_j}}-\frac{3\overline{\theta'\theta'}}{\rho_0}\frac{\partial}{\partial x_j}\left(\rho_0\overline{\theta'u_j'}\right)$$

Closures Needed

1) Closures for the effects of higher moments that are not predicted, e.g., as mentioned above, the fourth moments in a third-order closure model.

2) Closures for moments involving the pressure, which occur in the equations for moments that involve velocity components.

3) Closures for dissipation rates, which are especially important in the equations governing variances.

4) Closures to determine SGS phase changes (e.g., Sommeria and Deardorff, 1977; Mellor, 1977) and other microphysical processes (e.g., Larson et al., 2005), as well as radiative heating and cooling.

What is HOC good for?

- Flux parameterizations in models
- Interpretation of observations and high-resolution simulations

Both Chin-Hoh Moeng and Steve Krueger used HOC in their PhD work.

Issues

- Closures
- "Too statistical" -- no room for phenomenology
- Too complicated

Meanwhile...

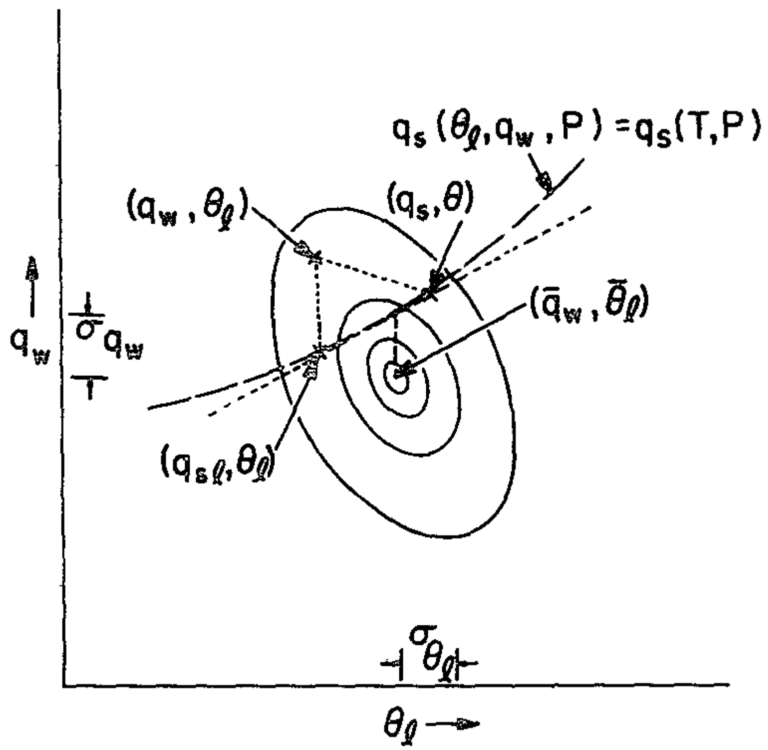
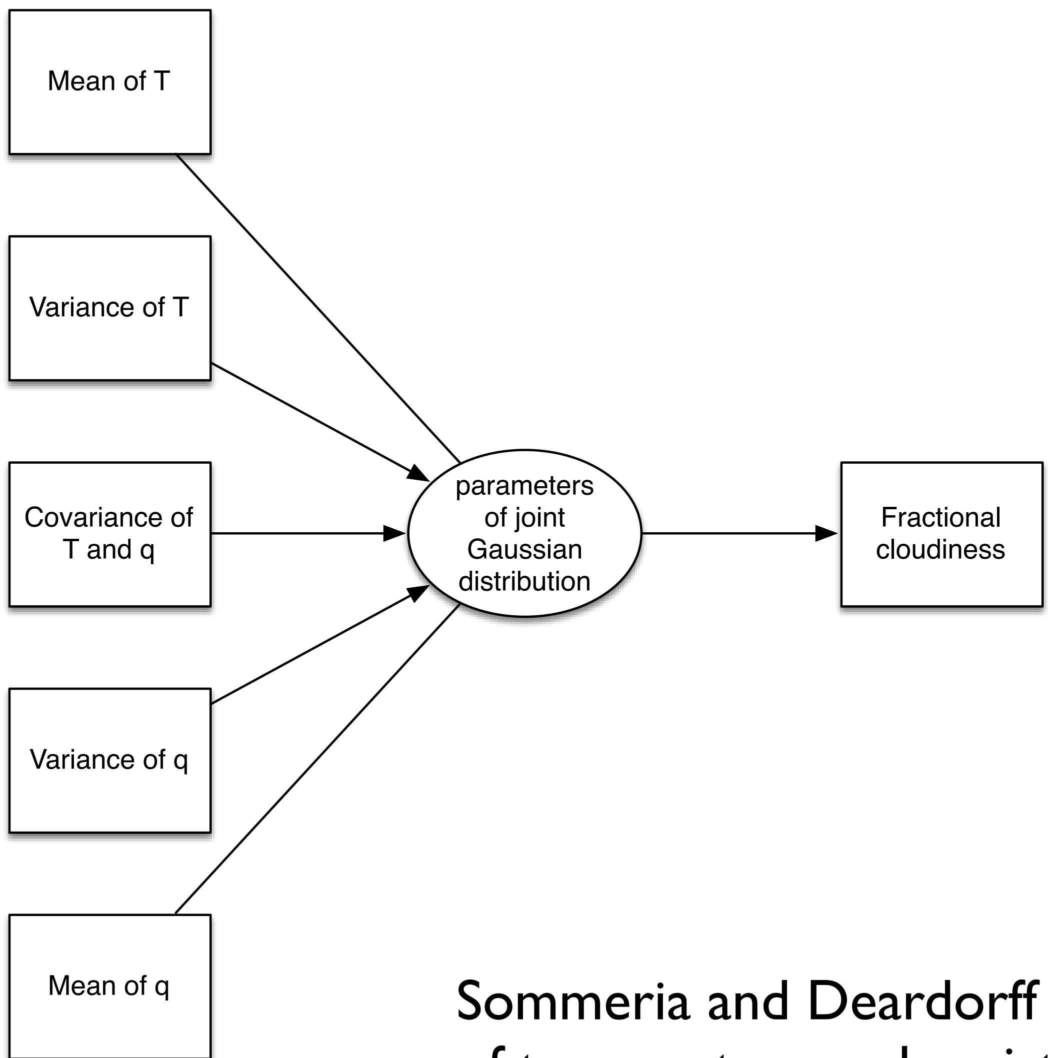


FIG. 1. Schematic diagram of the distribution of the variables q_w and θ_l inside a given grid volume.

Sommeria & Deardorff (1977) and Mellor (1977)

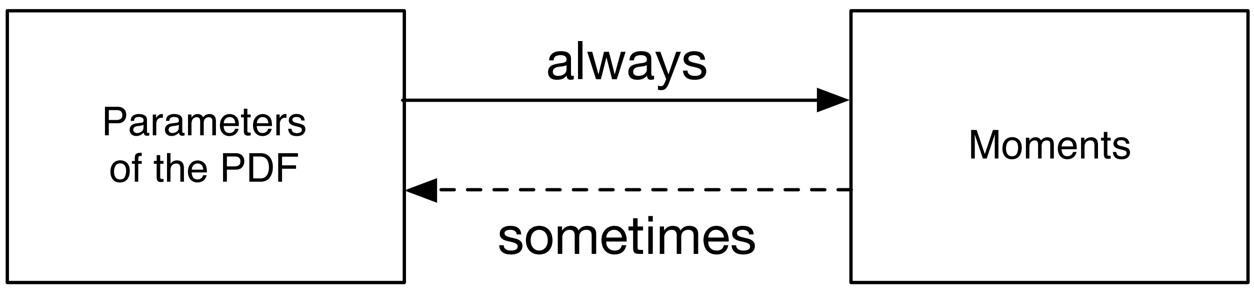
Their idea



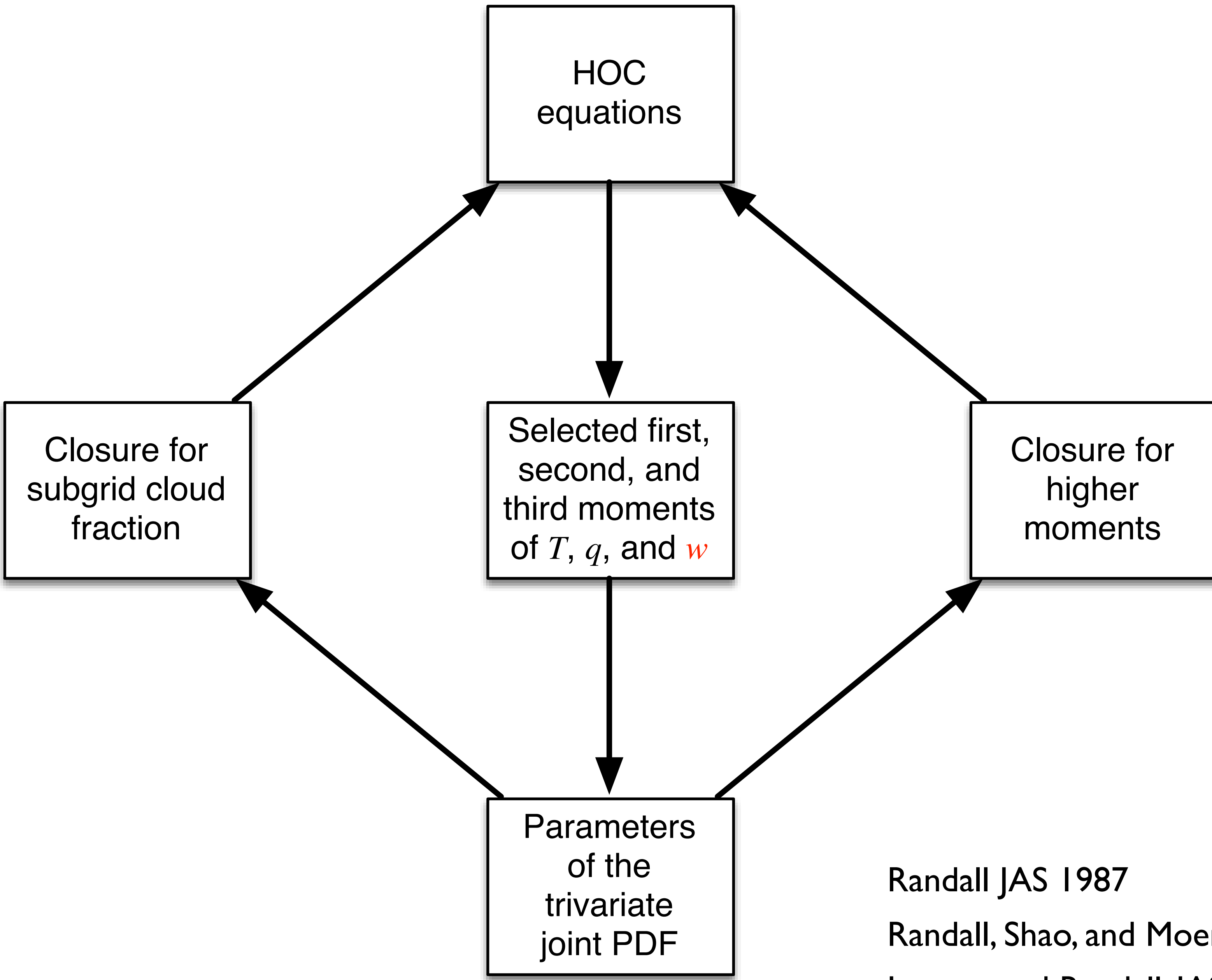
Sommeria and Deardorff used an *assumed joint distribution* of temperature and moisture.

They needed 2 first moments and 3 second moments to determine the parameters of the joint distribution.

Back and forth



Let's include w in the joint distribution.



Randall JAS 1987

Randall, Shao, and Moeng, JAS 1992

Lappen and Randall, JAS 2001

Closures Found

1) Closures for the effects of higher moments that are not predicted, e.g., as mentioned above, the fourth moments in a third-order closure model. ✔

2) Closures for moments involving the pressure, which occur in the equations for moments that involve velocity components.

3) Closures for dissipation rates, which are especially important in the equations governing variances.

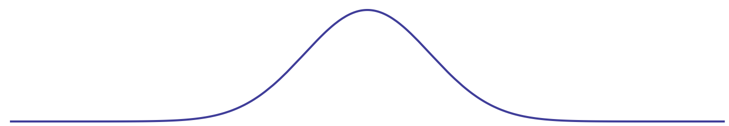
4) Closures to determine SGS phase changes (e.g., Sommeria and Deardorff, 1977; Mellor, 1977) and other microphysical processes (e.g., Larson et al., 2005), as well as radiative heating and cooling. ✔

Phenomenology

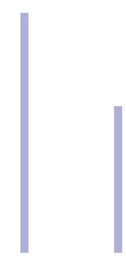
One Gaussian represents the clouds, and the other represents the environment.

Which assumed PDF?

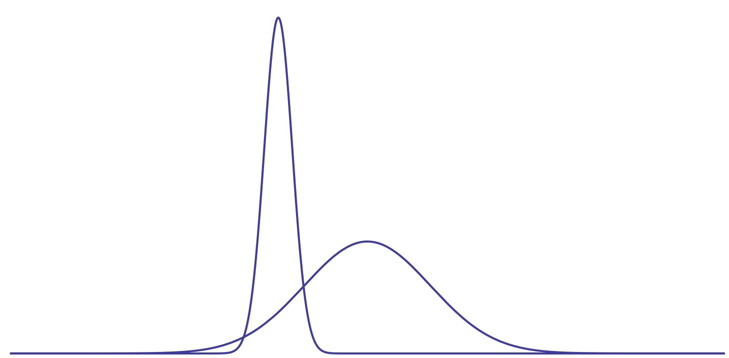
- Gaussian?
  No third moments.

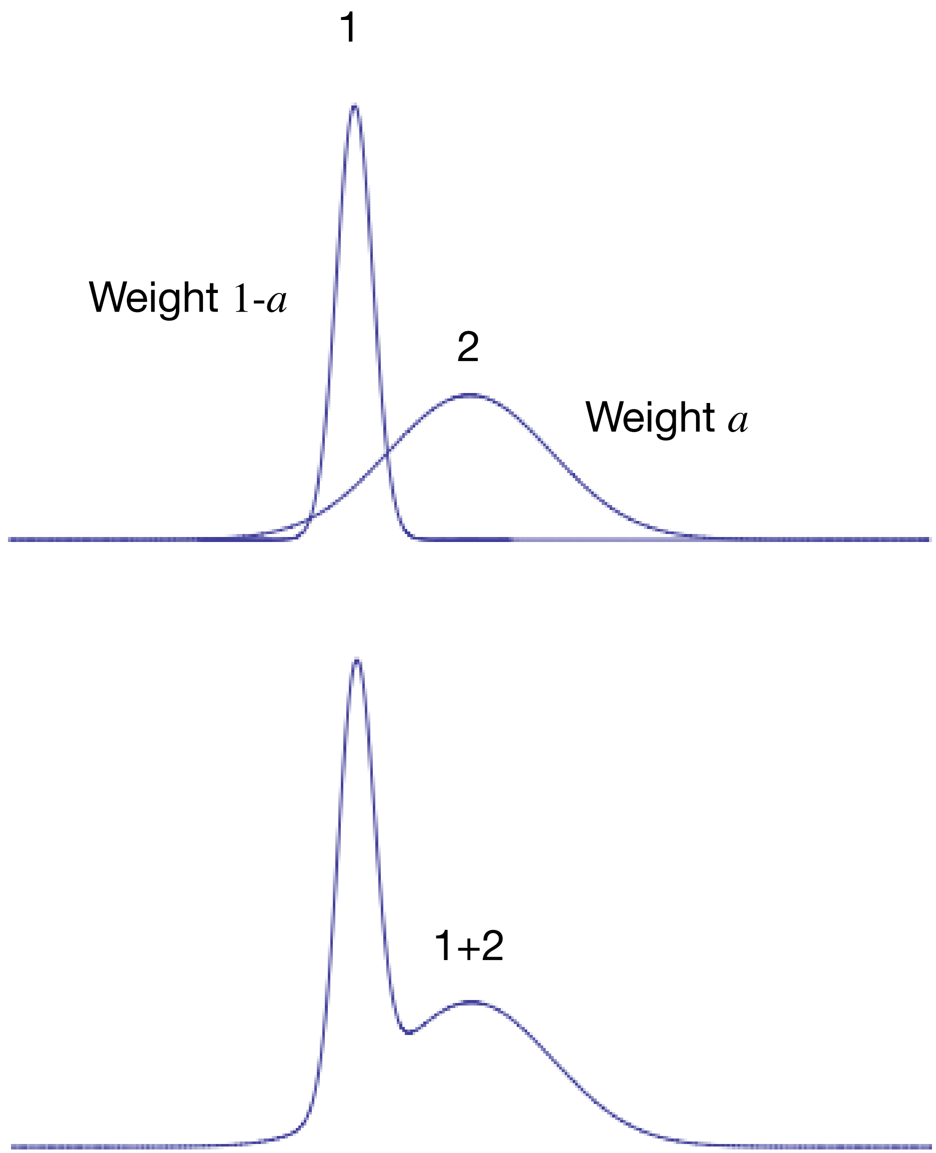


- Two delta functions?
  Not realistic enough.



- Two Gaussians?
  Good compromise,
  suggested by Lewellen and
  Yoh (1993) and adopted
  by Golaz et al., 2002.





We use trivariate double Gaussians, for w, T, and q.

Parameters of the trivariate PDF

a, -1

$\overline{w_1}, \overline{w_2}, \overline{T_1}, \overline{T_2}, \overline{q_1}, \overline{q_2}$, -6

$\overline{(w')_1^2}, \overline{(w')_2^2}, \overline{(T')_1^2}, \overline{(T')_2^2}, \overline{(q')_1^2}, \overline{(q')_2^2}$, -6

$\left(\overline{w'T'}\right)_1, \left(\overline{w'T'}\right)_2, \left(\overline{w'q'}\right)_1, \left(\overline{w'q'}\right)_2, \left(\overline{q'T'}\right)_1, \left(\overline{q'T'}\right)_2$, -6

Total: 19

How are we going to deal with this?

Which moments are important?

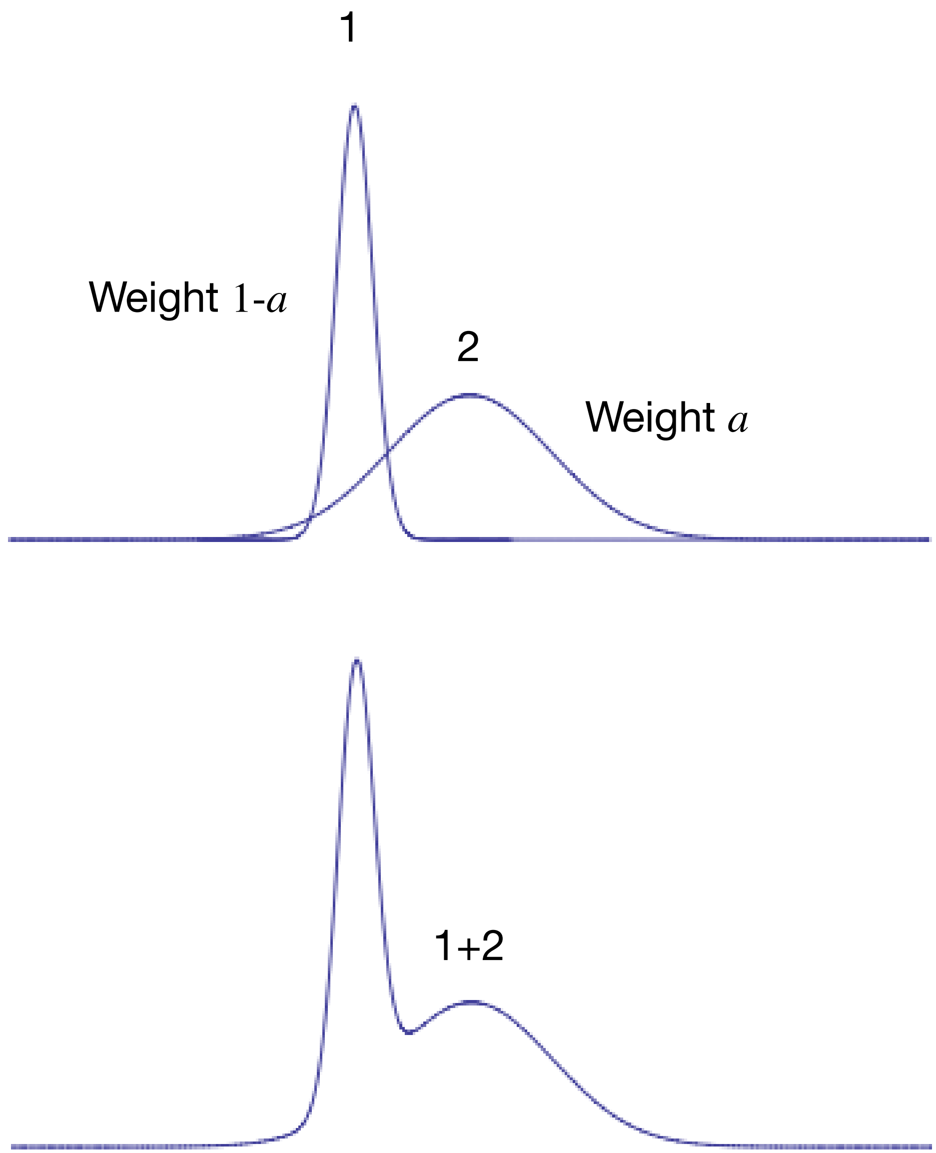
- Needed in HOC equations, directly, *or*
- Needed to determine the parameters of the PDF

Fluxes are needed in the first moment equations.

$$\overline{w'\theta'} \qquad \overline{w'q'}$$

The third moments measure the "distance" between the Gaussians.

$$\overline{w'w'w'} \qquad \overline{q'q'q'} \qquad \overline{\theta_l'\theta_l'\theta_l'}$$



The third moments measure the “distance” between the Gaussians.

Third moments rule.

It turns out that the six plume-scale means and the weight, a, can be determined using just four third-moments, in addition to the three first-moments. It is not necessary to predict any second-moments.

$$\overline{w'w'w'}\,,\ \overline{T'T'T'}\,,\ \overline{q'q'q'}\,,\ \overline{w'T'q'}$$

The sub-plume-scale second moments can and should be parameterized in terms of the plume-scale first moments. The full second moments can then be computed.

I will provide more details on Thursday morning.

Parameters of the trivariate PDF

Determine by predicting three first moments and four third moments

$$a \text{ , -1}$$

$$\overline{w}_1 \text{ , } \overline{w}_2 \text{ , } \overline{T}_1 \text{ , } \overline{T}_2 \text{ , } \overline{q}_1 \text{ , } \overline{q}_2 \text{ , -6}$$

$$\overline{(w')_1^2} \text{ , } \overline{(w')_2^2} \text{ , } \overline{(T')_1^2} \text{ , } \overline{(T')_2^2} \text{ , } \overline{(q')_1^2} \text{ , } \overline{(q')_2^2} \text{ , -6}$$

$$\left(\overline{w'T'}\right)_1 \text{ , } \left(\overline{w'T'}\right)_2 \text{ , } \left(\overline{w'q'}\right)_1 \text{ , } \left(\overline{w'q'}\right)_2 \text{ , } \left(\overline{q'T'}\right)_1 \text{ , } \left(\overline{q'T'}\right)_2 \text{ ,-6}$$

Total: 19

Parameterize (phenomenology)

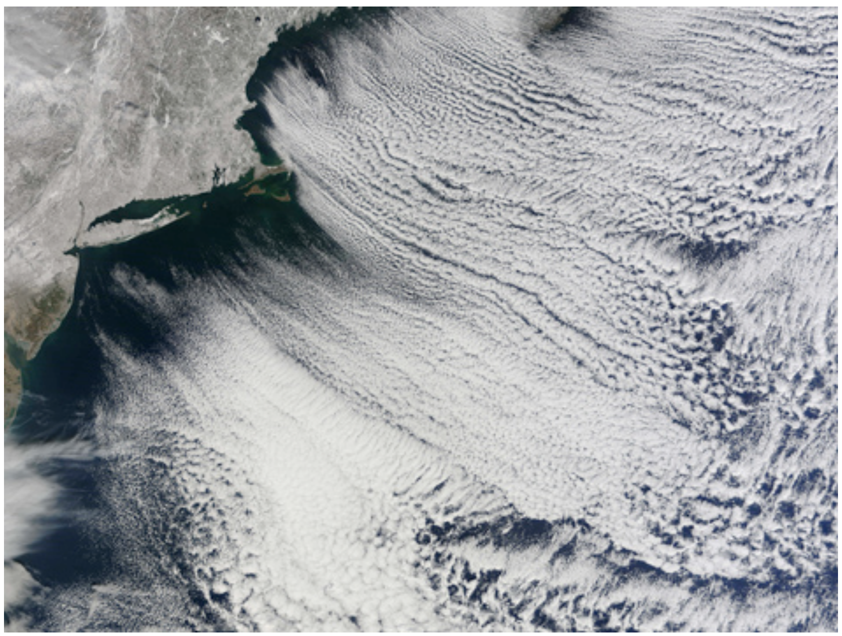
Issues

- Momentum fluxes?
- Deep convection?
- Gravity waves?

Momentum

$T, q,$ and w are not enough.

What about the momentum fluxes?



Pesky pressure terms are prominent in the second-moment equations for the momentum fluxes.

For the momentum flux, eddy size, shape, and orientation matter

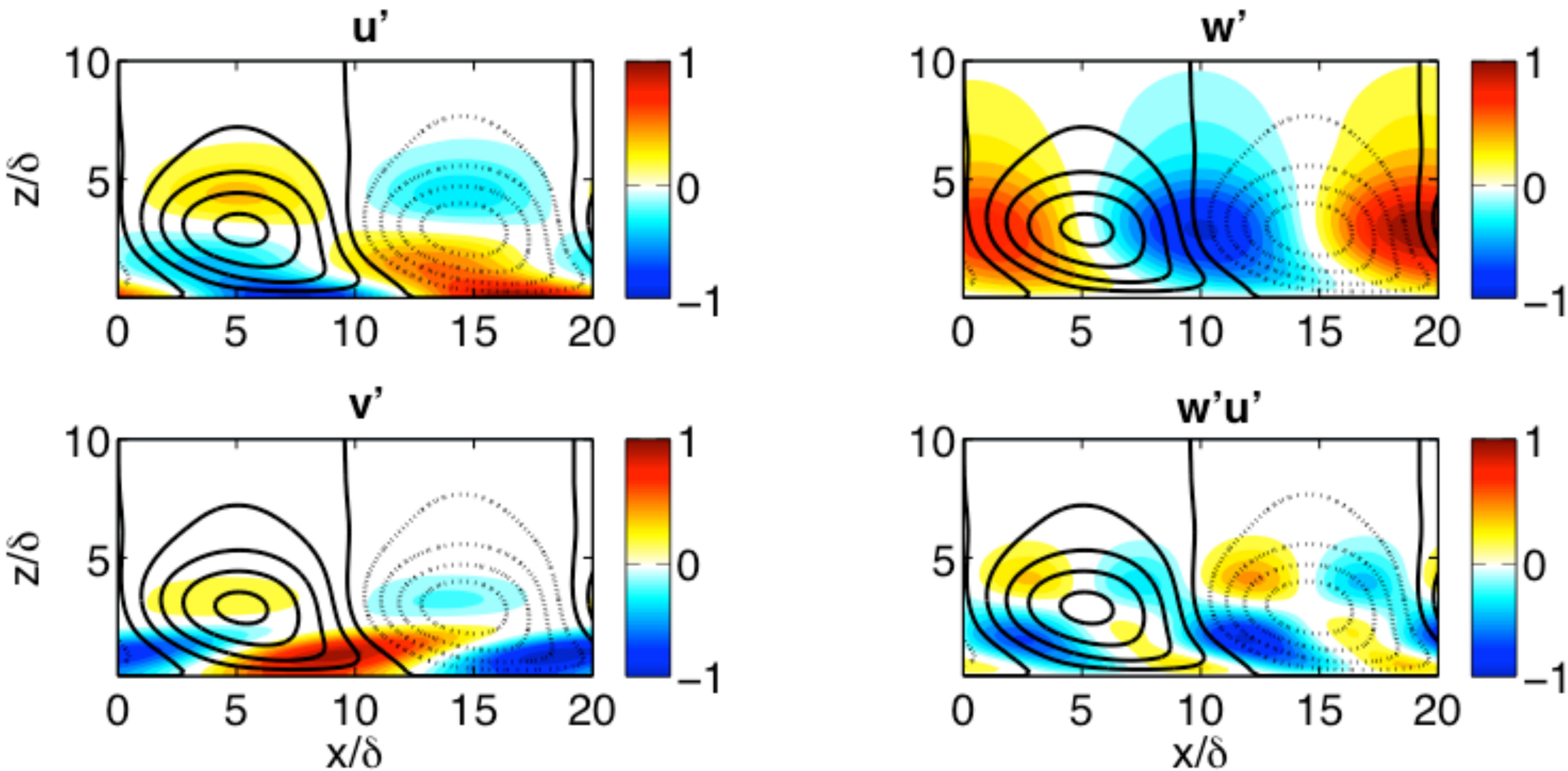
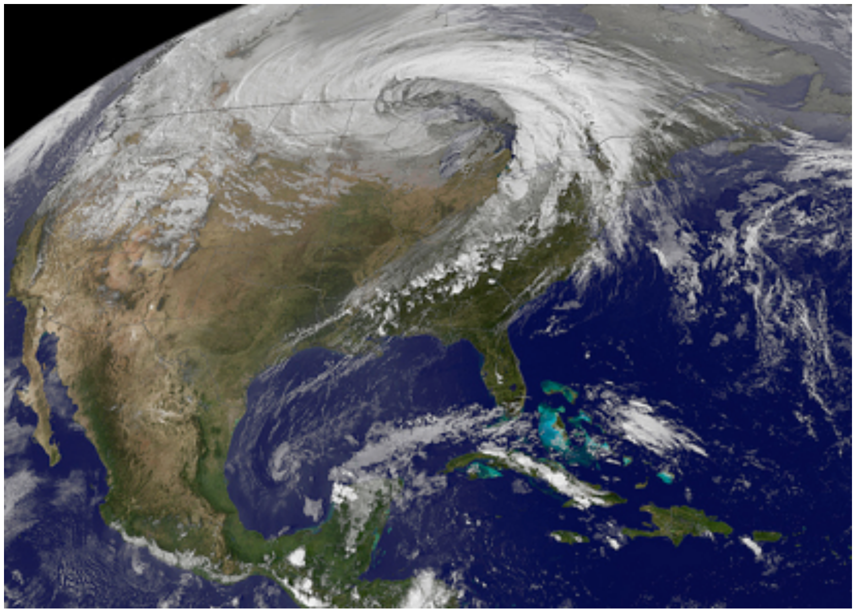


Figure from http://www.po.gso.uri.edu/Numerical/tropcyc/rolls.html

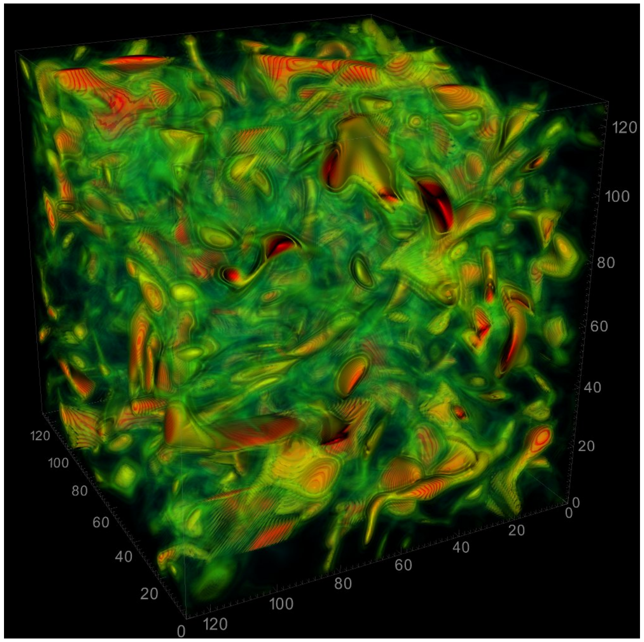
Maybe vorticity can help us with momentum.



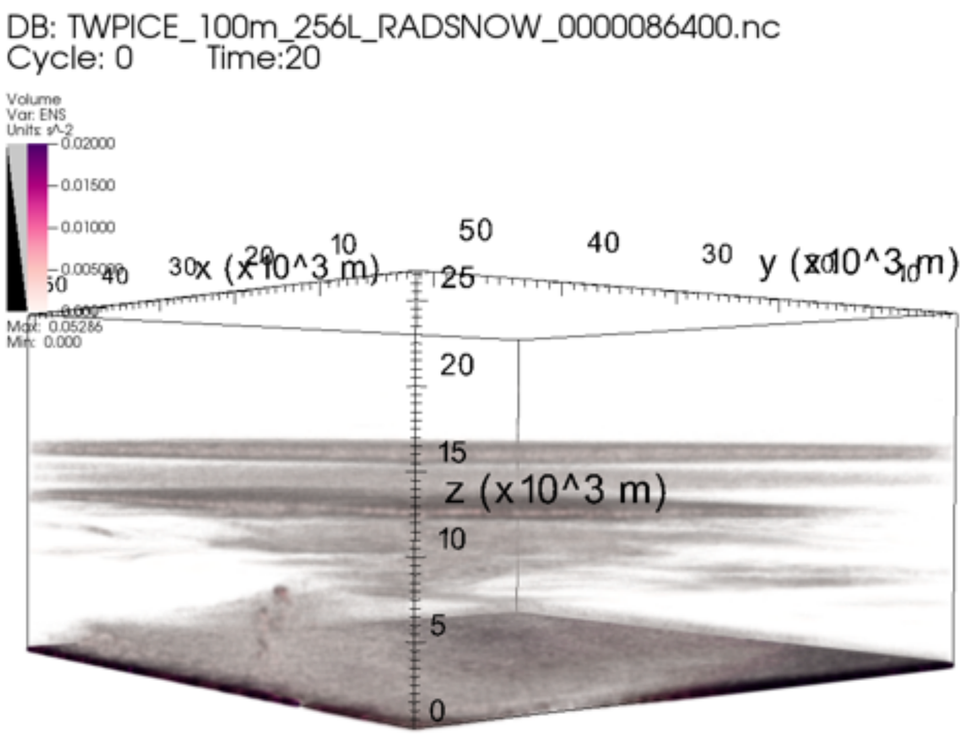
Weather is dominated by vorticity dynamics.

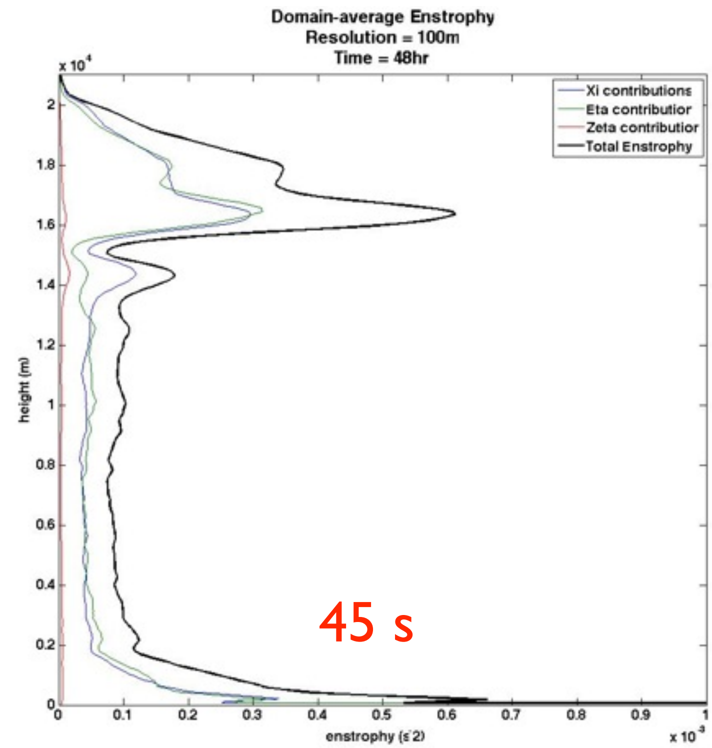
Enstrophy

- The ratio of kinetic energy to enstrophy defines a length scale. Eddy size and shape?
- The reciprocal of the square root of the enstrophy is a time scale that may be useful in a dissipation closure.
- The contribution to the enstrophy from the vertical component of the vorticity may be useful for severe weather forecasting.



Enstrophy in Giga-LES

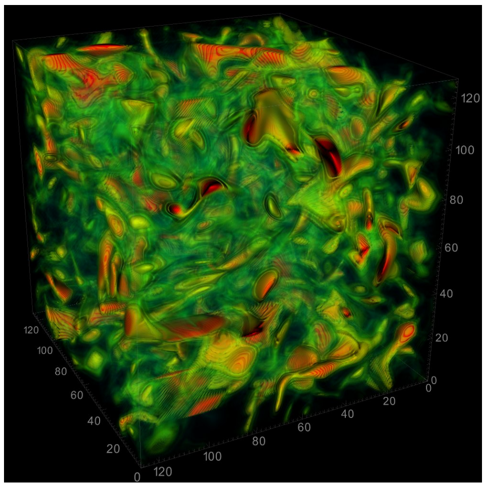




Almost all of the enstrophy is in the horizontal vorticity.

Plots from Don Dazlich

Is HOC a “theory of everything?”



Turbulence

Deep convection

Gravity waves

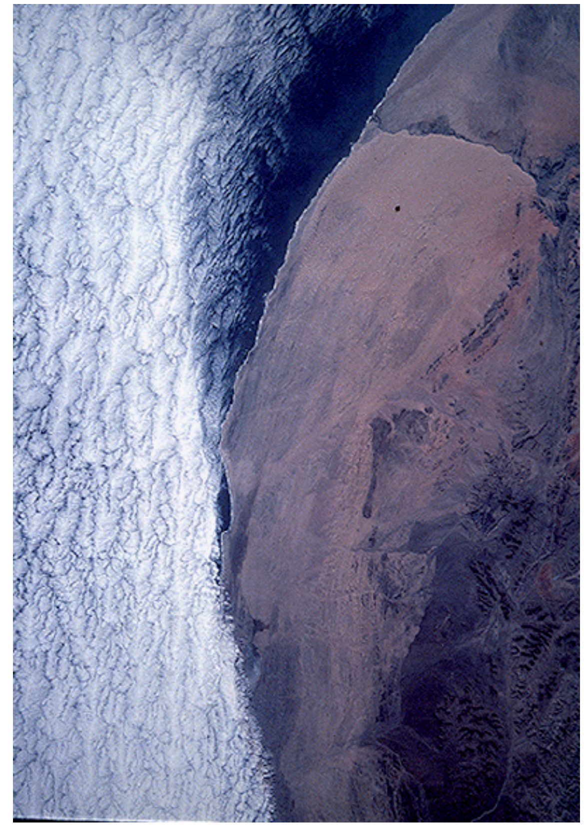
To represent all of these things, a very general closure would be needed.

From the STC pre-proposal, 2003

“To maximize the utility of the MMF, we must develop improved versions of its parameterizations of micro- physics, turbulence, and radiation. … Initial work on turbulence will explore multiple alternative approaches including higher-order closure….”

Four implementations

- Cheng and Xu (IPHOC)
- Krueger & Bogenschutz (SHOC)
- Larson and Zhang (CLUBB)
- Firl & Randall (THOR)



All four use assumed double Gaussian joint distributions for temperature, moisture, and vertical velocity.

The details differ considerably.

Conclusions

- Fluxes have kept me busy for a long time.
- It is useful to combine HOC with assumed distributions.
- HOC is now being used in the MMF, with the important (and expected) benefits.
- We need a good way to bring momentum fluxes into this framework. Can moments involving vorticity help?
- Deep convection? Gravity waves?