Super-parameterization and Cloud-Climate feedbacks

Multi-scale Modeling of Atmospheric Processes (MMAP)
'water vapor, confessedly the greatest thermal absorbent in the atmosphere, is dependent on temperature for its amount, and if another agent, as CO$_2$ not so dependent, raises the temperature of the surface, it calls into function a certain amount of water vapor which further absorbs heat, raises the temperature and calls forth for more vapor....'

T.C. Chamberlain in his 1905 correspondence to G.G Abbott
On a molecule by molecule basis, the ‘thermal absorbent effects’ of water in condensed phase >1000 times that of water in gaseous phase.

While it is (reasonably) clear what is meant by water vapor, it is less clear for clouds – amount, height, water/ice amount, optical properties, microphysics, etc.

The dependence of ‘clouds’ on temperature and surface temperature specifically is not well understood and to first order is governed by large scale fluid motions of the atmosphere.
Unlike water vapor, clouds impart an almost equal effect of solar energy balance. This adds to the complexity of the problem.

Clouds and water vapor are intimate (inseparable?) components of the hydrological cycle and couple to other of processes and thus contribute to other climate feedbacks.
There are two perspectives to the climate change problem, one of energy and one of water.

Perhaps the umbrella theme of MMAP concerns the atmospheric branch of the water cycle.

Perhaps then one of the goals of MMAP is towards understanding and (eventually) quantifying the climate sensitivity.

MMAP (perhaps) also provides an organizing principle for addressing/formulating the science under this perspective.
The energy/water perspective of climate change

Examples of ‘feedback’ systems that exemplify the multi-process nature of the problem and issues

The convection/stratiform conundrum

Key Issues, steps forward and journey with MMAP
Key climate feedbacks lie here
An energy perspective

Smagorinsky 1975 NRC report, range of uncertainty 1.5-4.5K

Same prescribed forcing (Courtesy, B. Soden)
Atmos energy loss $\sim 100 \text{ Wm}^{-2}$

$\sim$in balance with latent heating $\sim 80/90 \text{ Wm}^{-2}$

To First Order

Thus changes to atmospheric radiative heating $\Rightarrow$

changes in precipitation

Clouds are the principal modulator of this heating
CMIP analyses, B. Soden
Strat. WV
1.4 ± 200%

Upper Trop. WV
570 ± 100%

Lower Trop. WV
10400 ± 30%

Strat. Cloud Ice
0.71 ± 100%

Cloud Ice
1.9 ± 40%

Precip. Ice
35 ± 100%

Precip. Liquid
14 ± 50%

Cloud Liquid
1.9 ± 40%

L’Ecuyer and Stephens, 2003
Example 1: The Cloud Optical Depth Feedback

Optical depth $\propto$ LWP (Stephens, 1978)

LWP $\propto$ Optical depth $\propto$ cloud albedo
(Stephens, 1978)

$T \propto$ LWP $\propto$ cloud albedo $\propto$ cloud albedo $\propto$ T

Paltridge, 1980; Charlock, 1982; Sommerville & Remer, 1984;......
TABLE 1. Measured Mean Annual Cloud Liquid Water Content Over the U.S.S.R as a Function of Temperature Range [from Feigelson, 1978]

<table>
<thead>
<tr>
<th>Temperature Range, °C</th>
<th>Water Content, $10^{-3}$ kg m$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20 to -25</td>
<td>0.09</td>
</tr>
<tr>
<td>-15 to -20</td>
<td>0.12</td>
</tr>
<tr>
<td>-10 to -15</td>
<td>0.15</td>
</tr>
<tr>
<td>-5 to -10</td>
<td>0.17</td>
</tr>
<tr>
<td>0 to -5</td>
<td>0.21</td>
</tr>
<tr>
<td>5 to 0</td>
<td>0.26</td>
</tr>
<tr>
<td>10 to 5</td>
<td>0.28</td>
</tr>
<tr>
<td>15 to 10</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Our procedure is extremely simple. We note that cloud optical thickness is to a good approximation proportional to cloud liquid water content [Stephens, 1978]. Defining $f$ by

$$f = \frac{1}{L} \frac{\partial L}{\partial T}$$

(1)

where $L$ is cloud liquid water content and $T$ is temperature, we estimate that the observational data (Table 1) suggest $f = 0.04$ to $0.05$ for temperatures between $-25^\circ C$ and $+5^\circ C$, which is approximately the temperature range of the cloud-containing levels in our model. If cloud liquid water content $L$ scaled as saturation vapor pressure, as given by the Clausius-Clapeyron equation, we would expect $f = 0.08$ for temperatures near 263 K, for example. Our results are presented compactly in Table 2. The surface temperature warming
TABLE 2. Model Surface Temperature Warming $\Delta T$ Due to Doubling CO$_2$ Concentration as a Function of Cloud Liquid Water Content Dependence on Temperature $f$

<table>
<thead>
<tr>
<th>$f$, deg$^{-1}$</th>
<th>$\Delta T$, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.74</td>
</tr>
<tr>
<td>0.01</td>
<td>1.34</td>
</tr>
<tr>
<td>0.02</td>
<td>1.12</td>
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<tr>
<td>0.03</td>
<td>0.96</td>
</tr>
<tr>
<td>0.04</td>
<td>0.85</td>
</tr>
<tr>
<td>0.05</td>
<td>0.75</td>
</tr>
<tr>
<td>0.06</td>
<td>0.67</td>
</tr>
<tr>
<td>0.07</td>
<td>0.62</td>
</tr>
<tr>
<td>0.08</td>
<td>0.56</td>
</tr>
<tr>
<td>0.09</td>
<td>0.51</td>
</tr>
<tr>
<td>0.10</td>
<td>0.48</td>
</tr>
</tbody>
</table>

$L$ is cloud liquid water content, $T$ is temperature, and $f = (1/L) (\partial L/\partial T)$.

From this perspective the main result of our research is that temperature-dependent cloud optical thicknesses may act as a thermostat and provide a substantial negative feedback.
BUT

Many speculated cloud feedbacks ignore the contribution of term A (effects of changing circulation on clouds). This has led to substantial confusion and debate on the relevance of the given feedback.

Consider the liquid water feedback.

Tselioudis et al., 1992

Others since: Del Genio and Wolf, 2000
Example 2: Regulation of Tropical SSTs

In the paradigm of simple RCE, the tropical atmosphere acts like a runaway GH system.

A negative feedback occurs to constrain tropical SSTs.
Large-scale wind-driven evaporation (Priestly, 1964; Newell, 1979; Bates, 1999)

Enhanced emission to space in dry, subsidence regions (Pierrehumbert, 1995)

Convection-radiation interaction (Ramanathan and Collins, 1991; Lindzen et al., 2000)

A lesson here is that analyses of feedbacks probably cannot be quantified from observations alone – it has to involve a valid ‘theory’ - is SP-CGM such a theory?
The MJO example of a cloud-radiation-climate feedback system?

The Madden Julian Oscillation is a fundamental mode of variability – A mode neither well understood nor well represented in models.
Sea Surface Temperature at 1.78S, 150W

Wind Speed

200mb Temperature Anomaly

200mb Temperature Anomaly - SST Anomaly

Surface - 3km Column Water Vapor

MLS 200mb H2O Volume Mixing Ratio

Surface Heat Flux

Downward Shortwave Flux

Net Longwave Flux

Net Radiation

TOGA-COARE
Satellite climatology

TOVS

GPCP

Reynolds SST

ERS1
TRMM composite data
Summary comments:

The cloud climate problem is complicated by the fact that there are many processes and associated parameters that potentially give rise to a complicated system of intertwined feedbacks.

But there is much yet to understand at a very gross level.

Progress in the cloud parameterization problem is absolutely necessary if we are to demonstrate future progress in the cloud-climate problem.
The way forward is to gather an understanding using models that have a *demonstrated* ability to represent reality. This requires a carefully orchestrated marriage of models with observation. 

NWP and its ‘machinery’ (assimilation, forecast verification, analysis, etc.) has to play a critical/seminal role.

Therefore the ties between super-parameterization/climate modeling with NWP have to be strongly linked and clearly articulated.
Convection/stratiform separation

Convective □ hydrology

[Image of a faucet dripping]

Large scale □ energy balance

Circa, 1960/70s

Zonally averaged cloud prescribed (fixed) properties

Circa, 1980s

Cloud physics through emergence of prognostic schemes

Convective parameterizations while physically intuitive contain much empiricism
Historically, the artificial separation of convective & stratiform processes implies that energy balance and hydrological cycle are empirically decoupled.

Intuitively, super-parameterization (extended) offers a consistent framework to bridge this separation.

Modern-‘Classical’ parameterization too can bridge the separation requiring the specification of an ‘empirical’ detrainment.

Does SP move us more to a testable ‘theory’ that links convective with stratiform cloudiness?
Is MMAP intrinsically & demonstrably more accurate than comparative parameterization methods?

Use ARM data to quantify the stochastic component of cloud-radiation parameterization

Include this noise in CAM2.0

Conduct ensemble integrations
With fixed SST
Compare ensemble to ‘control’

Does MMAP lead to a reduction in the intrinsic parameterization noise of cloud parameterization?
MMAP science is central to modeling and understanding the atmospheric branch of the water cycle – it potentially offers an organizing principle for studying the water perspective of the climate system.
<table>
<thead>
<tr>
<th>Increasing Relevance</th>
<th>Increasing Statistical Significance</th>
</tr>
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<tbody>
<tr>
<td>( t &lt; # )</td>
<td>( \Delta_x &lt; \sigma_x )</td>
</tr>
<tr>
<td>insignificant</td>
<td>marginally significant</td>
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</table>

Total precip, 20% of control

Surface temperature, 1K vs. control
Super-parameterization

The cloud climate problem is complicated by the fact that there are many processes and associated parameters that potentially give rise to feedback.

Processes these are inevitably coupled to other processes and hence other feedbacks of the system.

Two key themes:

1. The way forward is to thoroughly test models and the representation of key processes- this requires a carefully created liaison between models and observation.
2. The way forward is develop models that have a demonstrated ability to represent reality.

This requires a carefully orchestrated liaison of models and observation.

NWP and its ‘machinery’ (assimilation, forecast verification, analysis, etc.) should play a critical/seminal role.

Therefore the ties between super-parameterization/climate modeling with the more operational global modeling of NWP have to be strongly linked.
Hypotheses deal with large, complex coupled systems that do not necessarily obey simple laws – must be wary of over-reliance of lack of simplicity for exclusion of hypotheses …..’simple is just simple’.
2. The GCM perspective

Convective [ ] hydrology  
Large scale [ ] energy balance

Circa, 1960/70s

Zonally averaged cloud prescribed (fixed) properties

Circa, 1980s

Cloud physics through emergence of prognostic schemes

Convective parameterizations remain largely empirical

Little connection between convective and large scale clouds – little connection precipitation and large scale cloudiness – precipitation efficiency
Specific Humidity as a control

CLOUDS & PRECIPITATION

CIRCULATION

ENERGY radiative & latent heating

Nauru

Kauai
Fluxes and Heating rates

Solar fluxes, upwelling TOA, sz=20

Solar fluxes, downwelling at surface, sz=20

Heating rates

Fluxes
“The researches of many commentators have already thrown much darkness on this subject, and it is probable that, if they continue, we shall soon know nothing about it…” *Mark Twain*
Historically, the artificial separation of convective & stratiform processes implies that energy balance and hydrological cycle are effectively decoupled.

Intuitively, super-parameterization (extended) offers a consistent framework to bridge this separation.

Modern-’Classical’ parameterization too can bridge the separation requiring the specification of an ‘empirical’ detrainment.

Does SP move us more to a testable ‘theory’?
2. The way forward is to gather an understanding using models that have a *demonstrated* ability to represent reality

This requires a carefully orchestrated marriage of models and observation.

NWP and its ‘machinery’ (assimilation, forecast verification, analysis, etc) has to play a critical/seminal role

Therefore the ties between super-parameterization/climate modeling with the more operational aspects of NWP have to be strongly linked and clearly articulated.