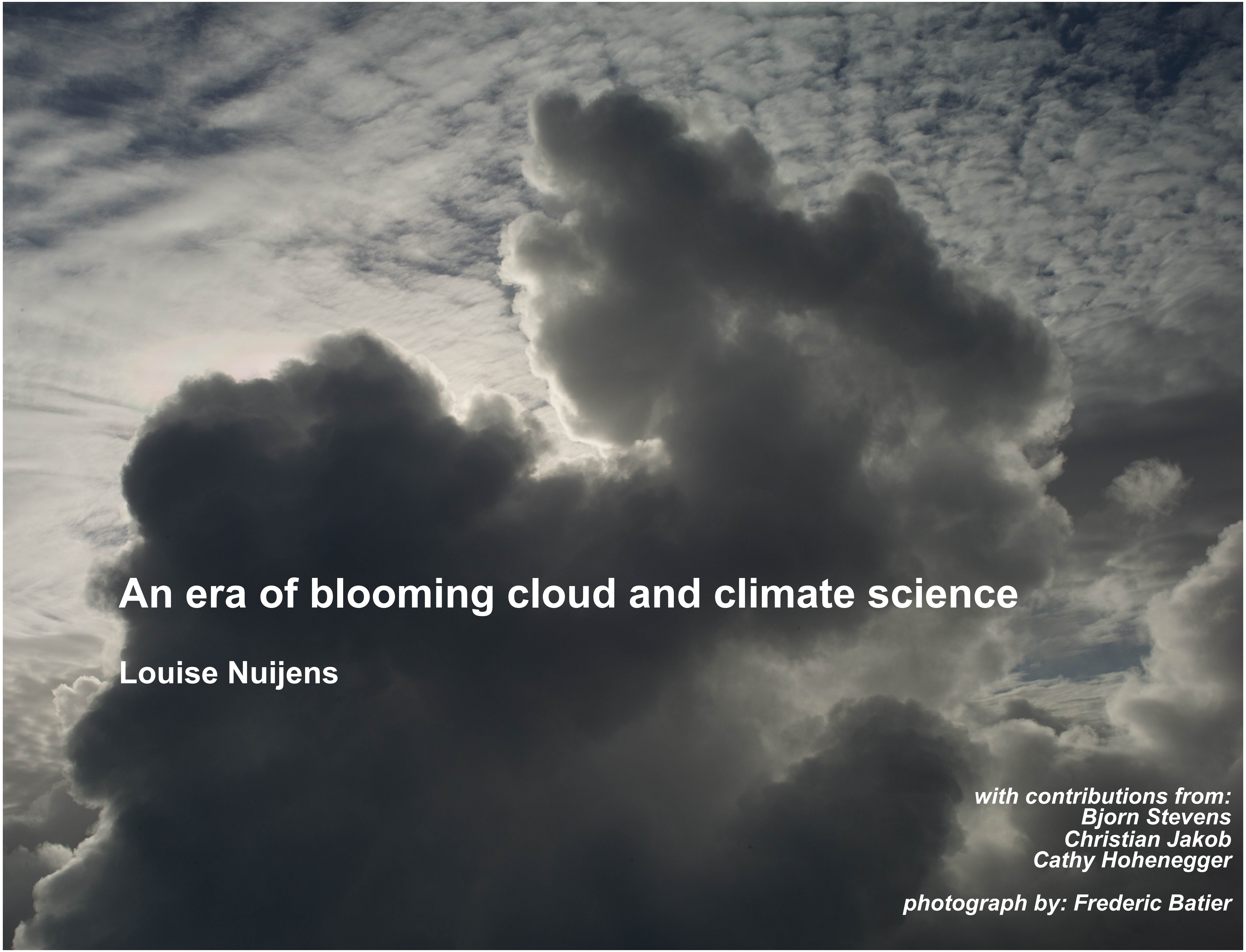

An era of blooming cloud and climate science

Louise Nuijens

with contributions from:
Bjorn Stevens
Christian Jakob
Cathy Hohenegger

photograph by: Frederic Batier

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TEMPERATURE RISING

Clouds' Effect on Climate Change Is Last Bastion for Dissenters

By JUSTIN GILLIS
Published: April 30, 2012 | 808 Comments

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LAMONT, Okla. — For decades, a small group of scientific dissenters has been trying to shoot holes in the prevailing science of climate change, offering one reason after another why the outlook simply must be wrong.

Enlarge This Image

Josh Haner/The New York Times
A technician at a Department of Energy site in Oklahoma launching a weather balloon to help scientists analyze clouds. More Photos »

Temperature Rising

Enigma in the Sky

This series focuses on the central arguments in the climate debate and examining the evidence for global warming and its

Over time, nearly every one of their arguments has been knocked down by accumulating evidence, and polls say 97 percent of working climate scientists now see global warming as a serious risk.

Yet in recent years, the climate change skepti[...] on one last argument that cannot be so readil[...] Their theory is that clouds will save us.

They acknowledge that the human release of [...] gases will cause the planet to warm. But they [...] clouds — which can either warm or cool the ea[...] depending on the type and location — will shi[...] way as to counter much of the expected tempe[...] and preserve the equable climate on which civ[...] depends.

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Warming World, Cloudy Days Are a Boon

[W]alsh | Friday, July 24, 2009

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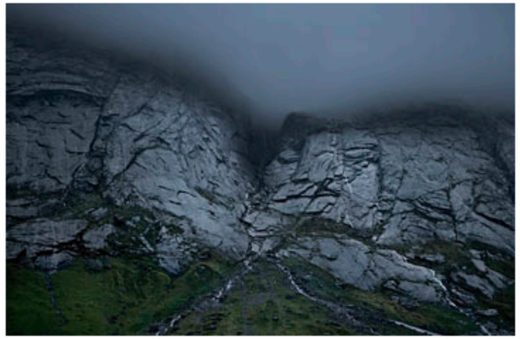
[...]o the atmosphere and the climate will get [...] that much is well established. But climate [...]d carbon aren't in a one-to-one [...]ip. If they were, climate modeling would be [...]ow much the globe will warm if we put a [...]ount of CO_2 into the air depends on the [...] of the climate. How vulnerable is the polar [...]w rapidly might the Amazon dry up; how [...] the Greenland ice cap disintegrate? That's [...]ls like those from the Intergovernmental [C]limate Change spit out a range of



PETER BOEL NIELSEN / GETTY

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Gesundheit | Umwelt | Geschichte

KLIMASZENARIEN

"Wir stehen vor einem Zielkonflikt"

Seite 2/3: Der Unsicherheitsfaktor Wolkenbildung

ZEIT: Wo liegen die größten Unsicherheiten?

Marotzke: Im Einfluss der Wolkenbildung. Sie ist einer der drei wesentlichen Faktoren bei der Erwärmung. Die anderen beiden sind sehr viel besser verstanden. Einer davon ist die reine Treibhauswirkung von Kohlendioxid, die bei einer hypothetischen Verdoppelung von CO_2 eine Erwärmung von etwas über einem Grad erzeugt; das basiert auf ganz schlichter Physik. Der andere Effekt ist die verstärkte Bildung von Wasserdampf bei höheren Temperaturen – der trägt ein weiteres Grad zum Treibhauseffekt bei. Dafür gibt es sehr robuste, übereinstimmende Beobachtungen.

ZEIT: Und was bewirken die Wolken?

The questions we all like to know

What is the impact of clouds on climate?

How do clouds change with changes in global mean sea surface temperature?

How do such changes alter the sensitivity of our climate to perturbations?

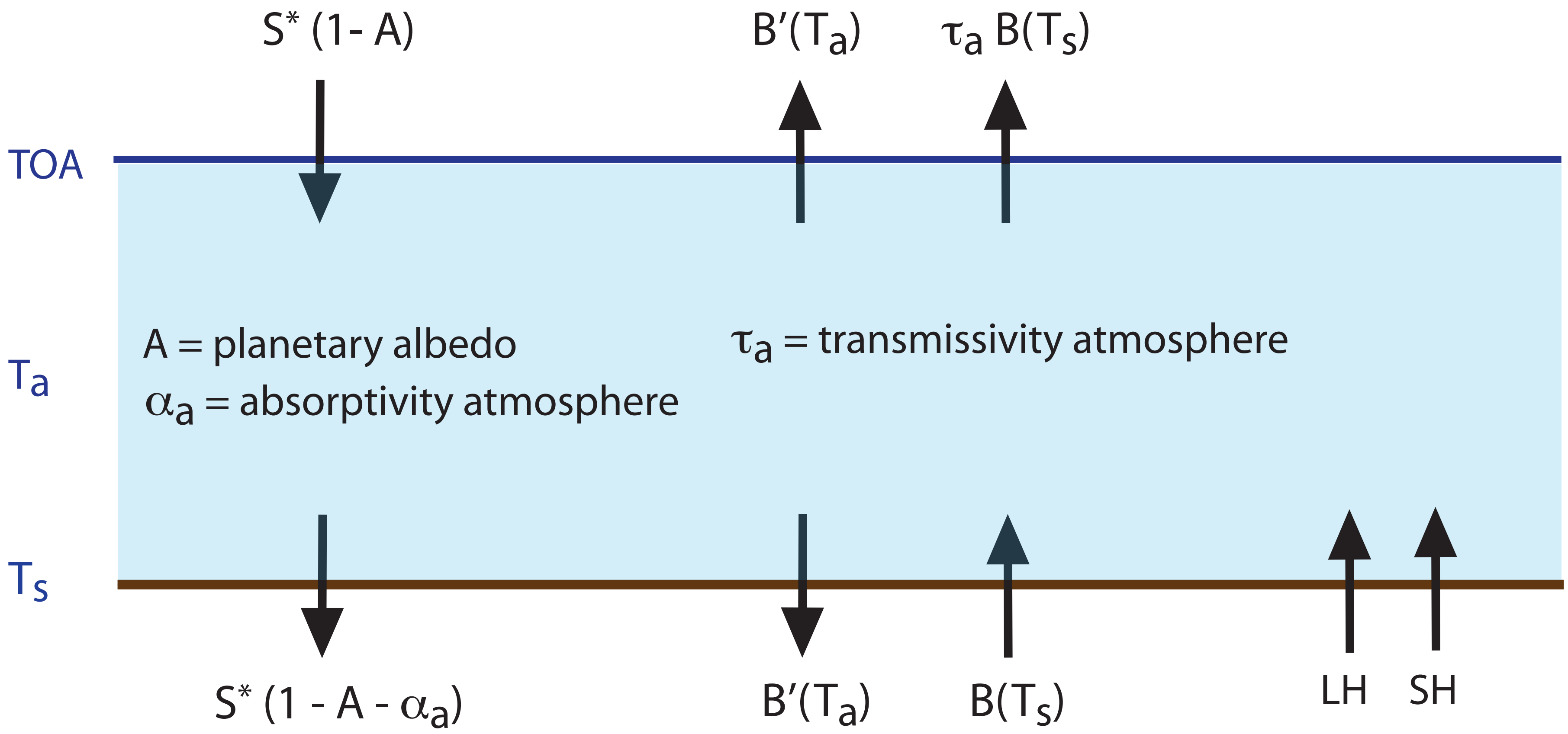
The questions we all like to know

What is the impact of clouds on climate?

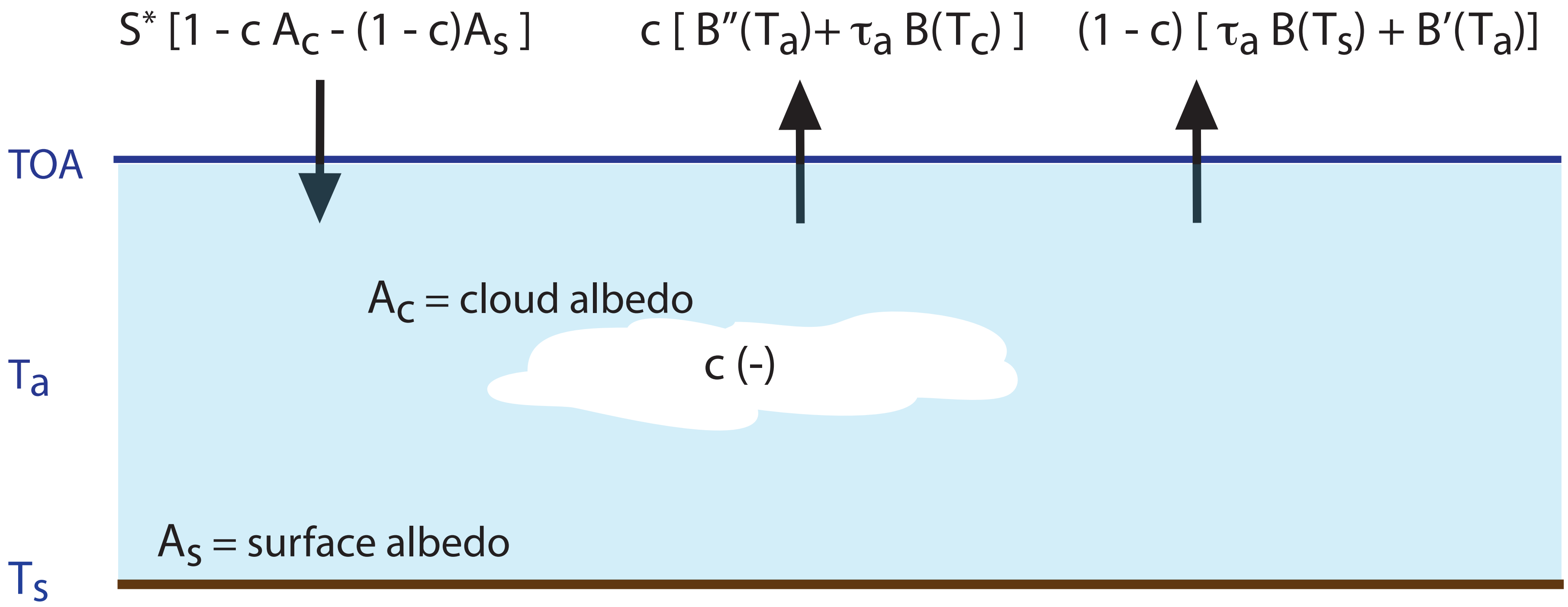
Part 1: Clouds in past and modern science

Part 2: Challenges in understanding the role of clouds in climate (change)

The Earth's energy balance

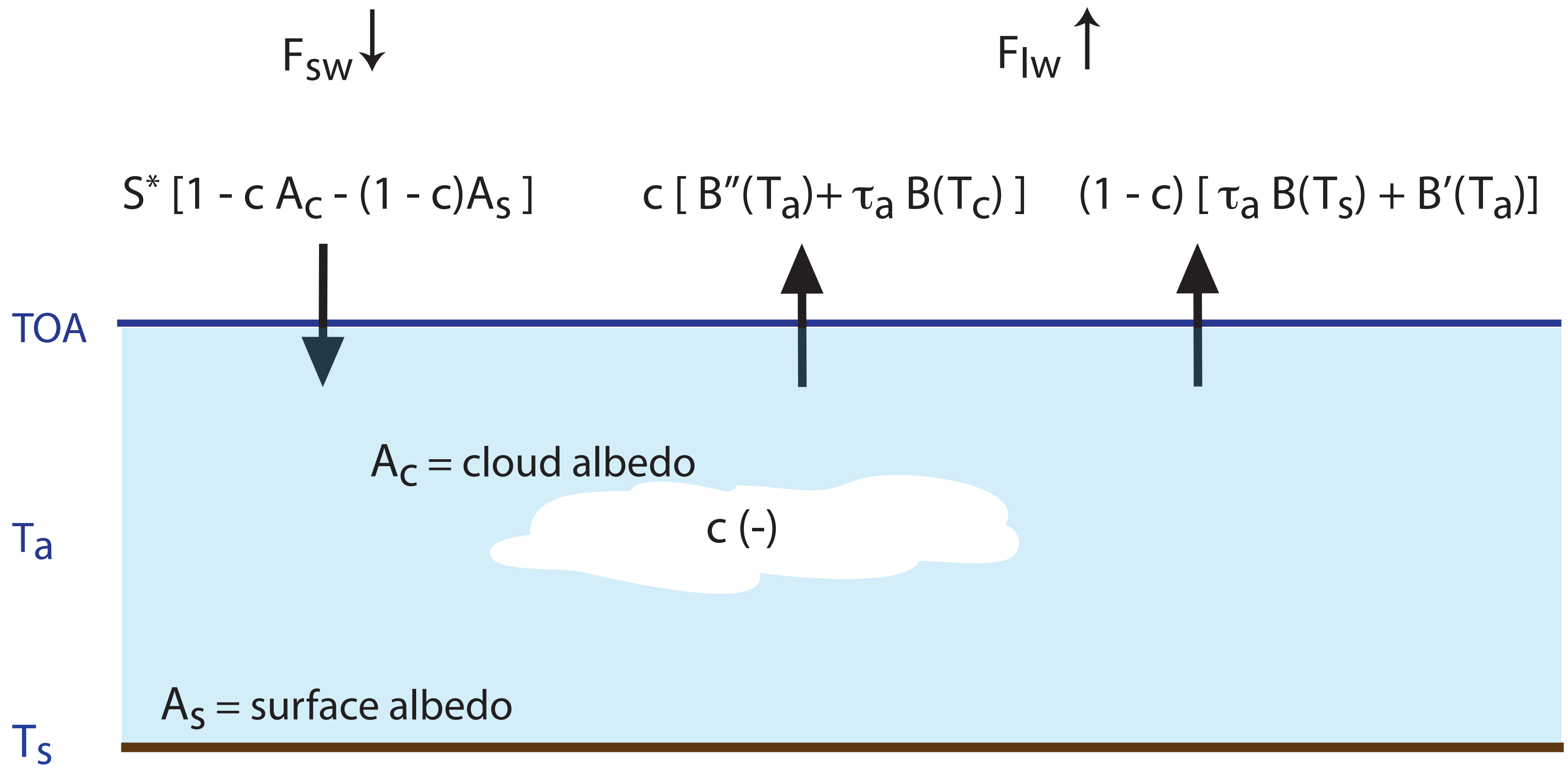


The cloud radiative effect



Schneider (1972)

The cloud radiative effect

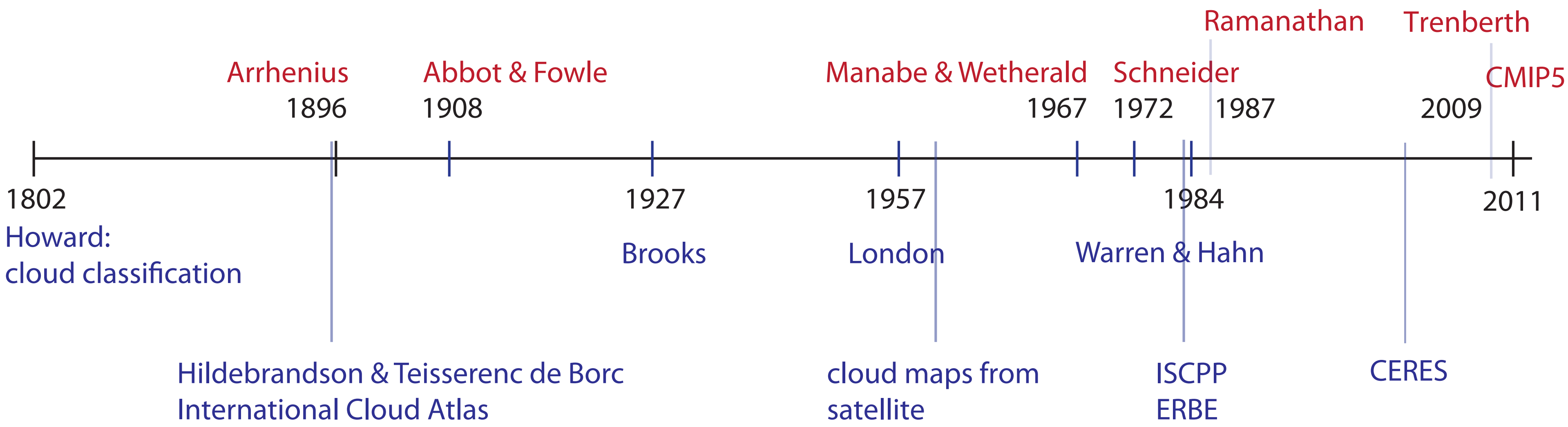


$$F^{\downarrow} = F_{sw}^{\downarrow} - F_{lw}^{\uparrow}$$

$$c\frac{\partial F^{\downarrow}}{\partial c} \equiv F^{\downarrow} - F^{\downarrow}(c=0)$$

Schneider (1972)

Building climatologies and (simple) climate models

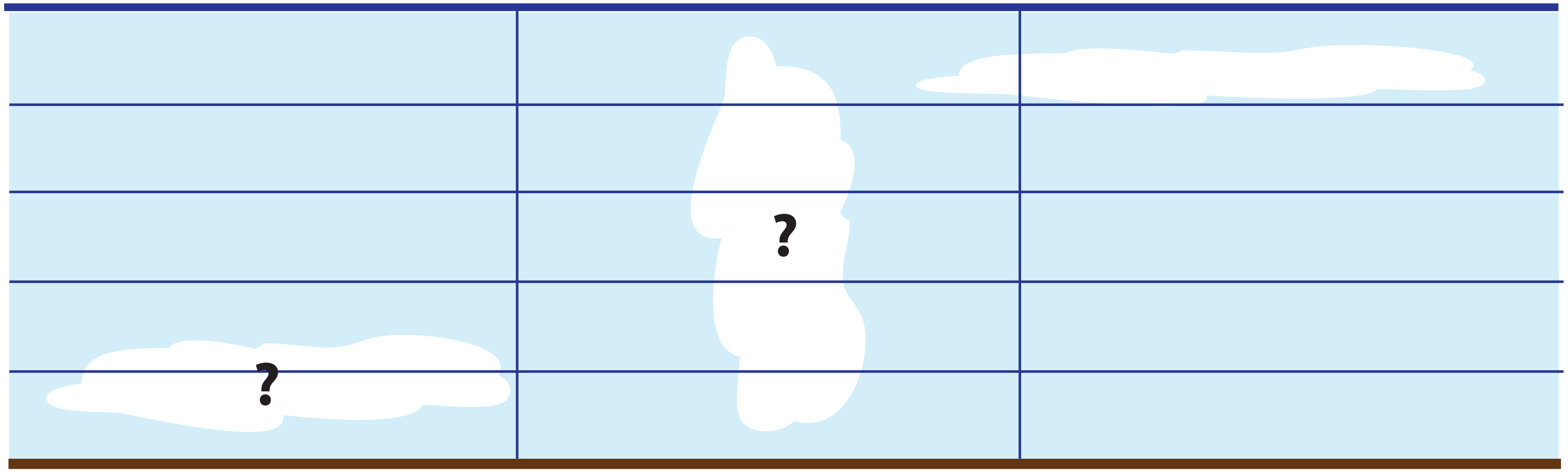


Hughes (1984)

Where to put the (relevant) clouds?

how much cloud is there?

how is that cloud distributed horizontally and vertically?



Flat Cloud

Ralph Abercromby:
"I shall pass by with barest notice the flat thin layers or sheets of clouds that are so often found in fine weather, and which are technically known as stratus-clouds. There is so little distinctive about this cloud form that it scarcely appears in folk-lore, though I believe that in Lancashire these flat sheets of condensed vapour are still called "the blanket of the sun". ... We will therefore pass on to the more striking and important (of clouds)"

Fig. 3.—Flat Cloud, usually known as Stratus. Taken in London.

Abercromby (1888)

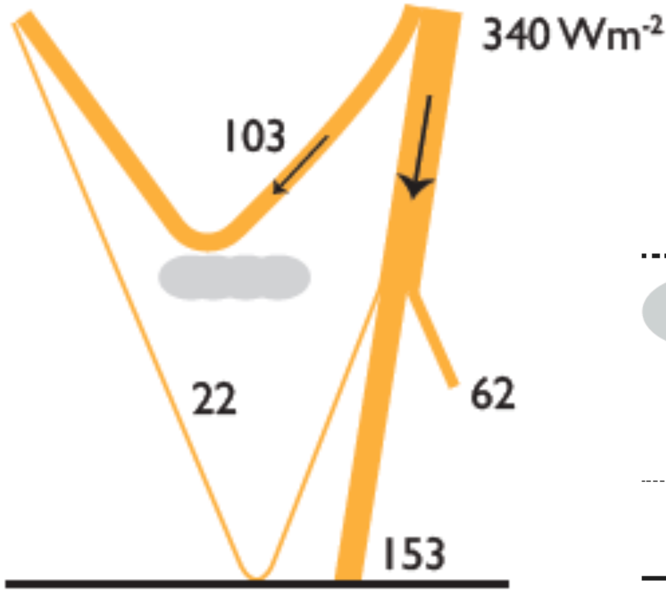
First estimates of the albedo

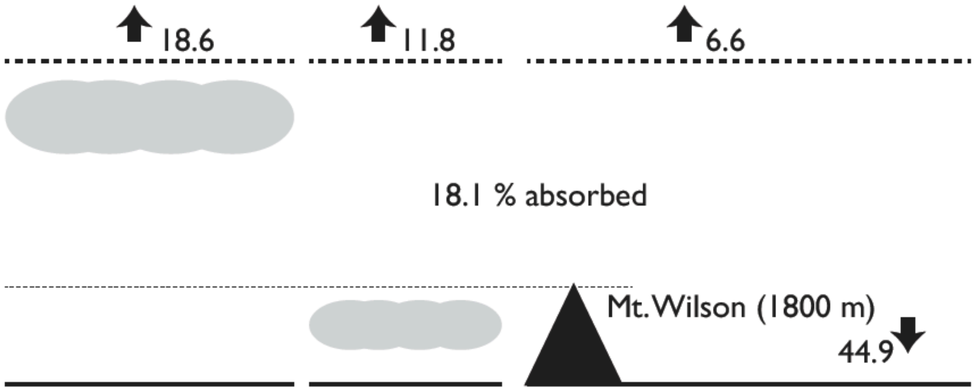
We have now shortly to consider the influence of the clouds. A great part of the earth's surface receives no heat directly from the sun, because the sun's rays are stopped by clouds. How great a part of the earth's surface is covered by clouds we may find from Teisserenc de Bort's work * on Nebulosity. From tab. 17 of this publication I have determined the mean nebulosity for different latitudes, and found:—

Latitude..	60.	45.	30.	15.	0.	−15.	−30.	−45.	−60.
Nebulosity.	0·603	0·48	0·402	0·511	0·581	0·463	0·53	0·701	

For the part of the earth between 60° S. and 60° N. we find the mean value 0·525, *i. e.* 52·5 per cent. of the sky is clouded. The heat-effect of these clouds may be estimated in

Albedo ~ 37%





Arrhenius (1896), Abbot and Fowle (1908), Figure by Bjorn Stevens

Three layers of cloud and albedo prescribed

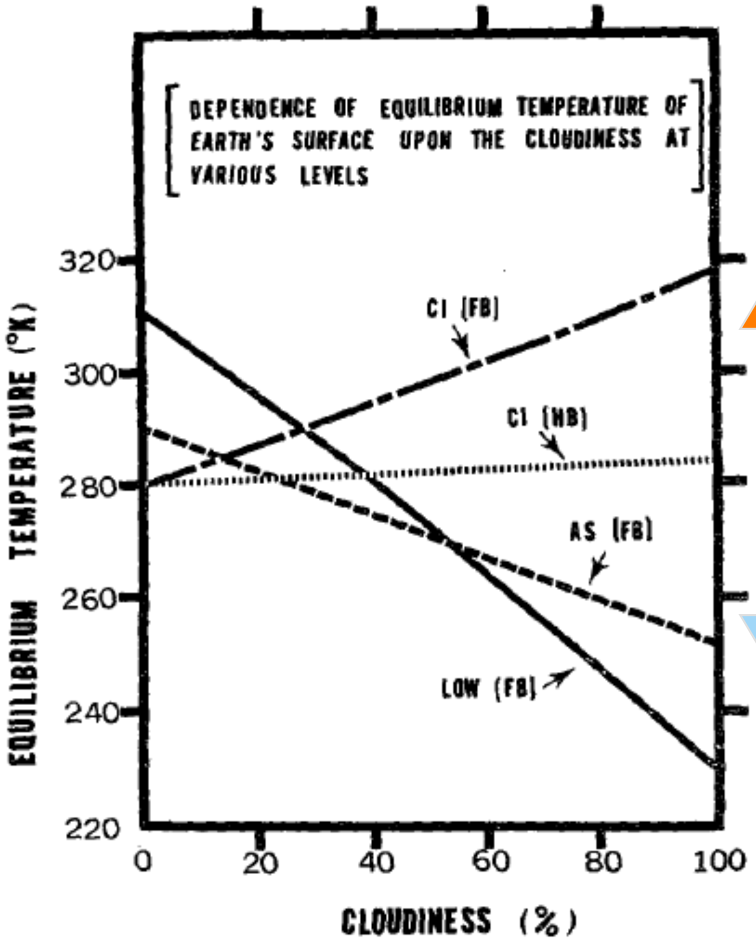


FIG. 20. Radiative convective equilibrium temperature at the earth's surface as a function of cloudiness (cirrus, altostratus, low cloud). FB and HB refer to full black and half black, respectively.

TABLE 1. Cloud characteristics employed in radiative convective equilibrium model.

Cloud	Height (km)	Amount	Albedo
High	10.0	0.228	0.20
Middle	4.1	0.090	0.48
Low			
top	2.7	0.313	0.69
bottom	1.7		

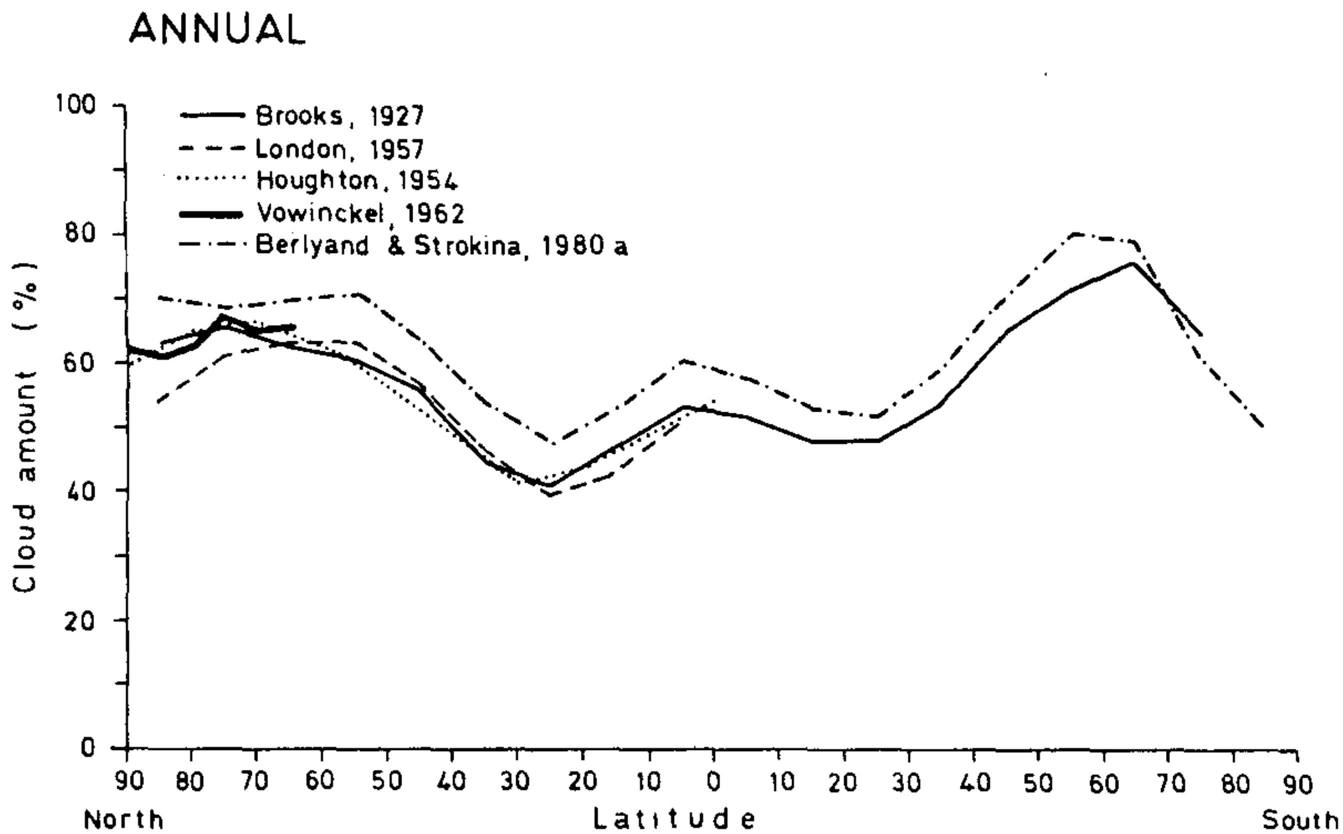
warming with increased high cloud

cooling with increased low cloud

Conclusion 6) "The effects of cloudiness … on the equilibrium temperature were also presented"

Manabe and Wetherald (1967)

Distribution of cloud amount



Hughes (1984)

Cloud amount was underestimated

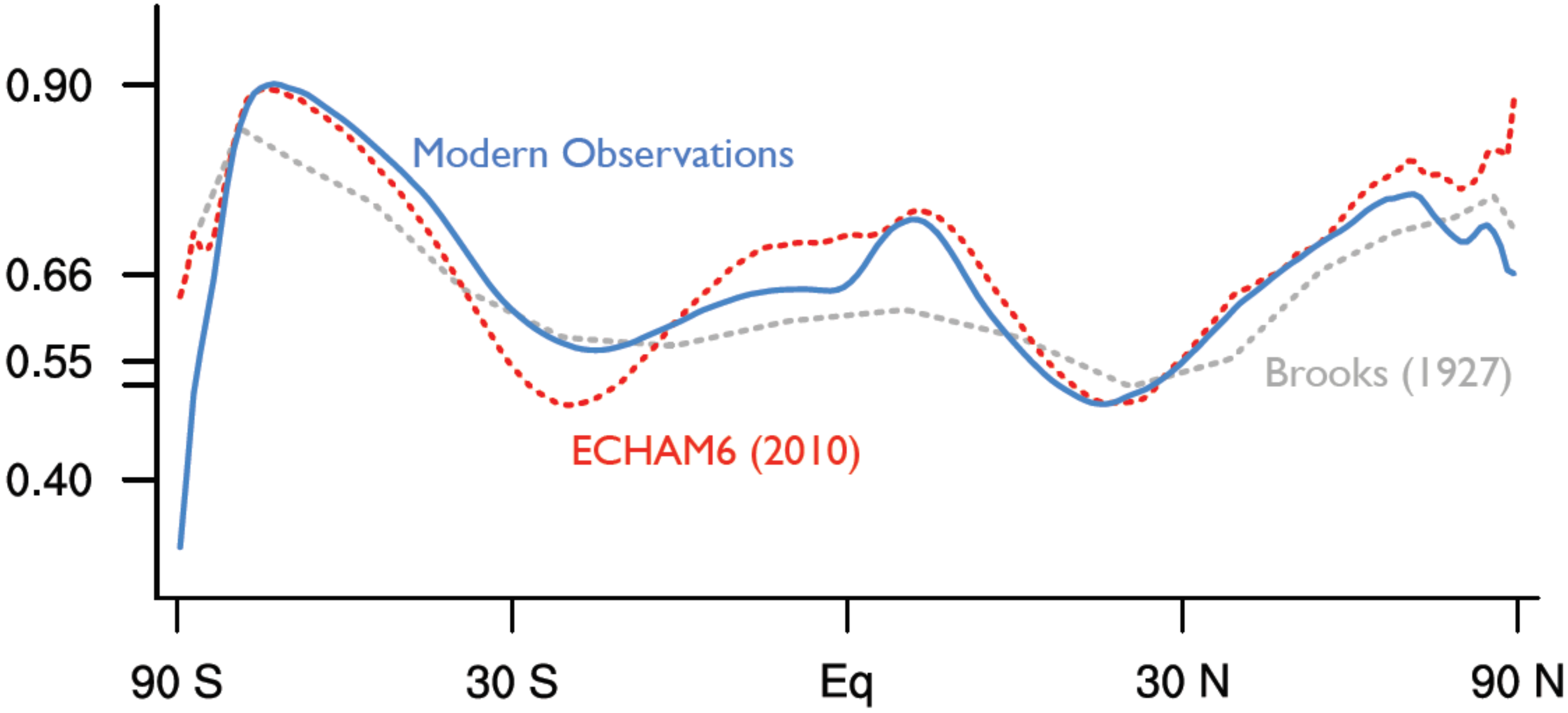


Figure by Bjorn Stevens

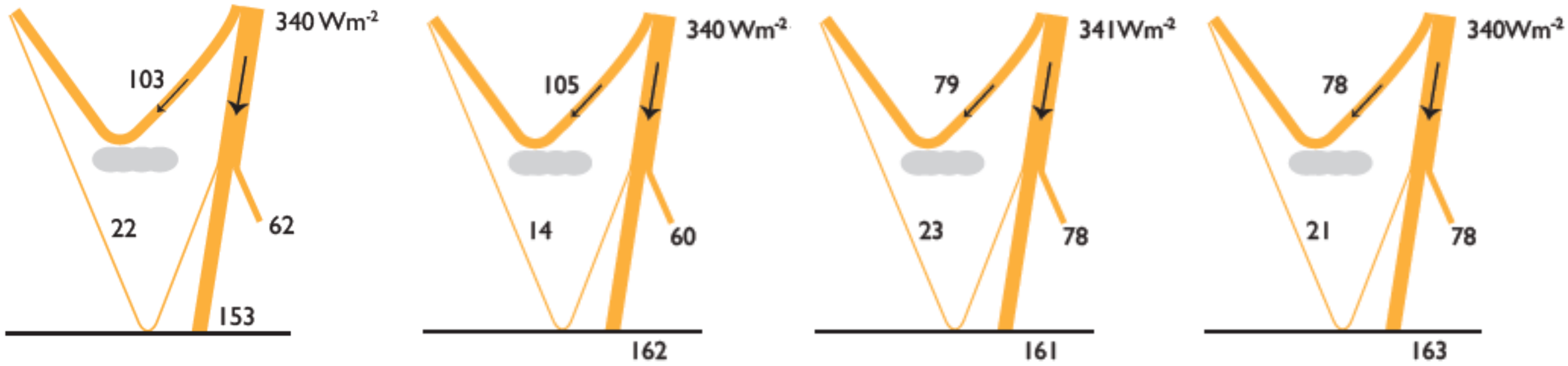
Surface-based observations

Cloud type	Annual average amount (%)	
	Land	Ocean
Fog	1	1
Stratus (St)	5	12
Stratocumulus (Sc)	12	22
Cumulus (Cu)	5	13
Cumulonimbus (Cb)	4	6
Nimbostratus (Ns)	5	5
Altostratus (As)	4	6
Altocumulus (Ac)	17	17
High (cirriform)	22	12
Total cloud cover	54	68
Clear sky (frequency)	22	3

during 1954-1997:
average percent of sky covered

Warren et al. (2007)

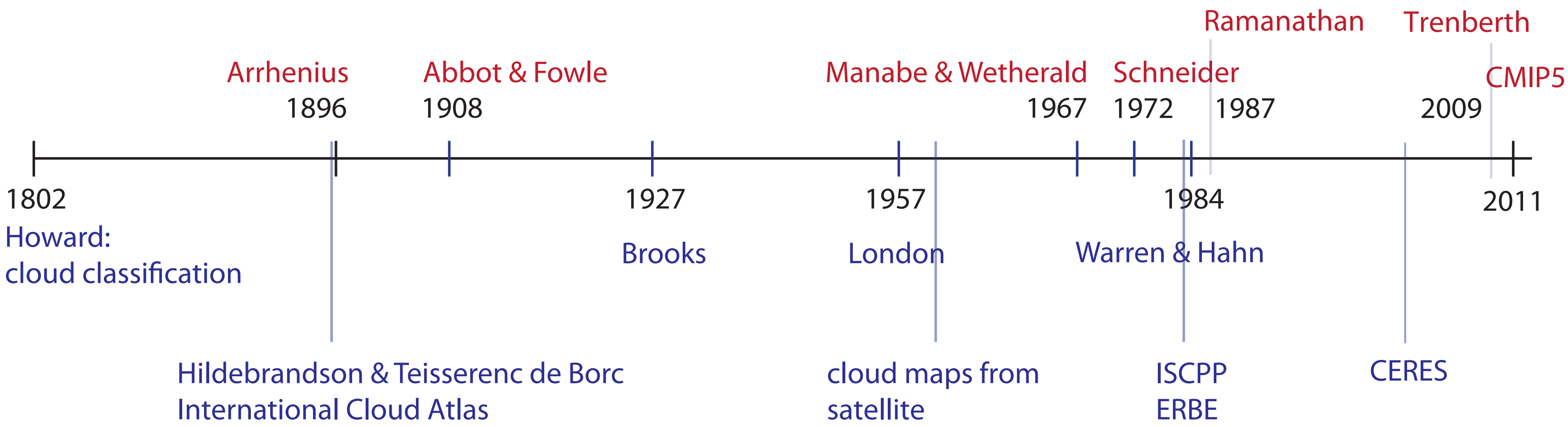
Early estimates of cloud albedo were not bad, but overestimated



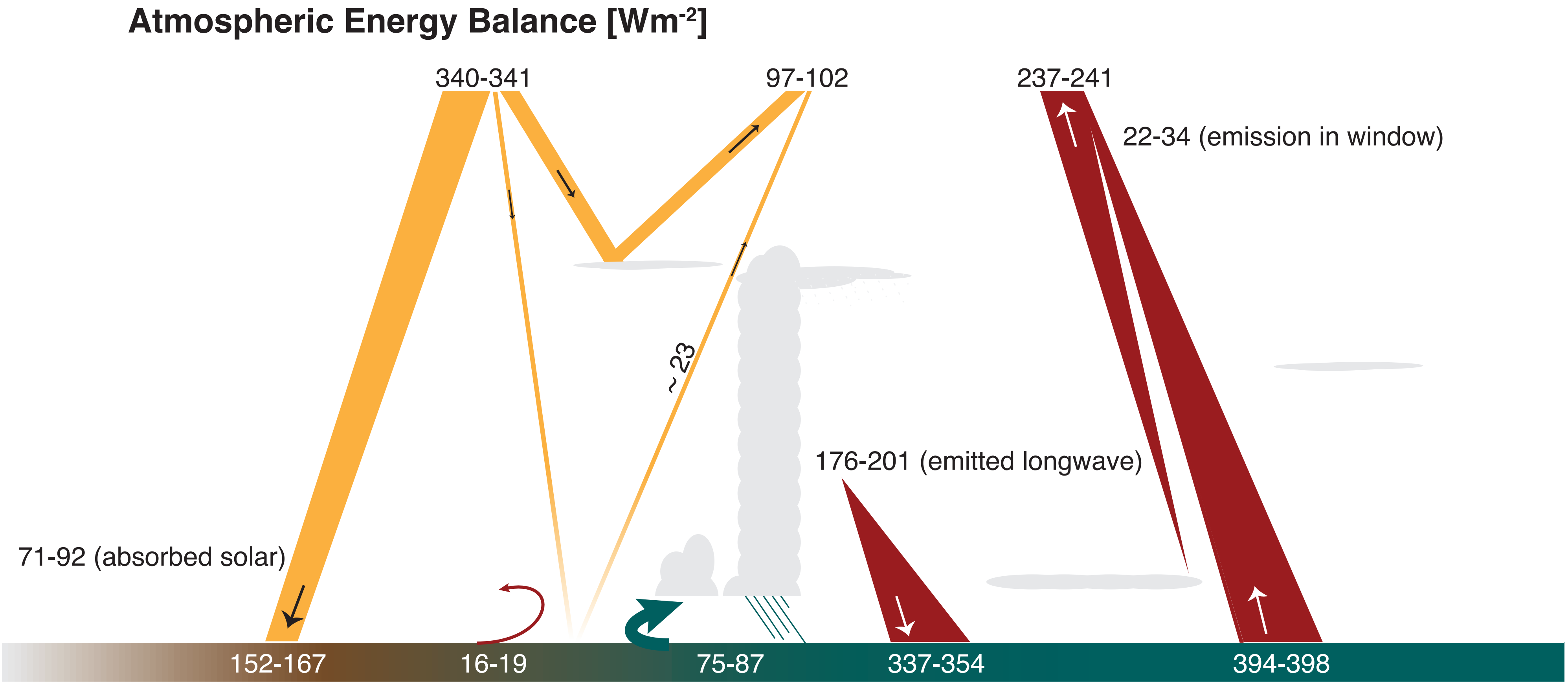
Arrhenius Abbot and Fowle (1908)	London (1957)	Trenberth (2009)	CERES (2009)
37%	35%	29%	29%

Stevens and Schwartz (2012)

A break from cloud science?

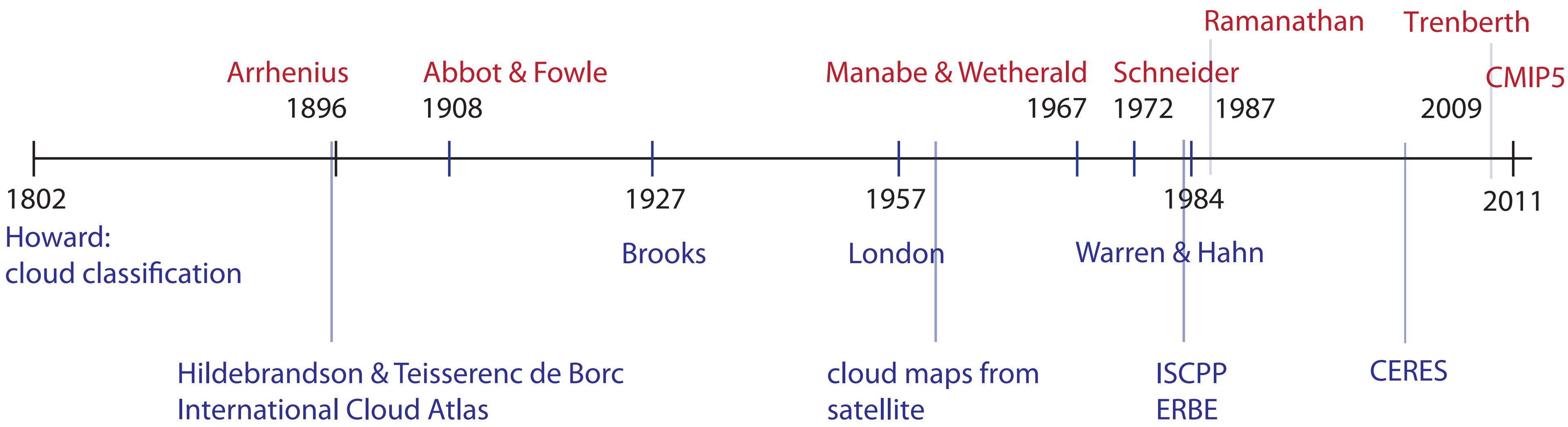


The Earth's energy balance

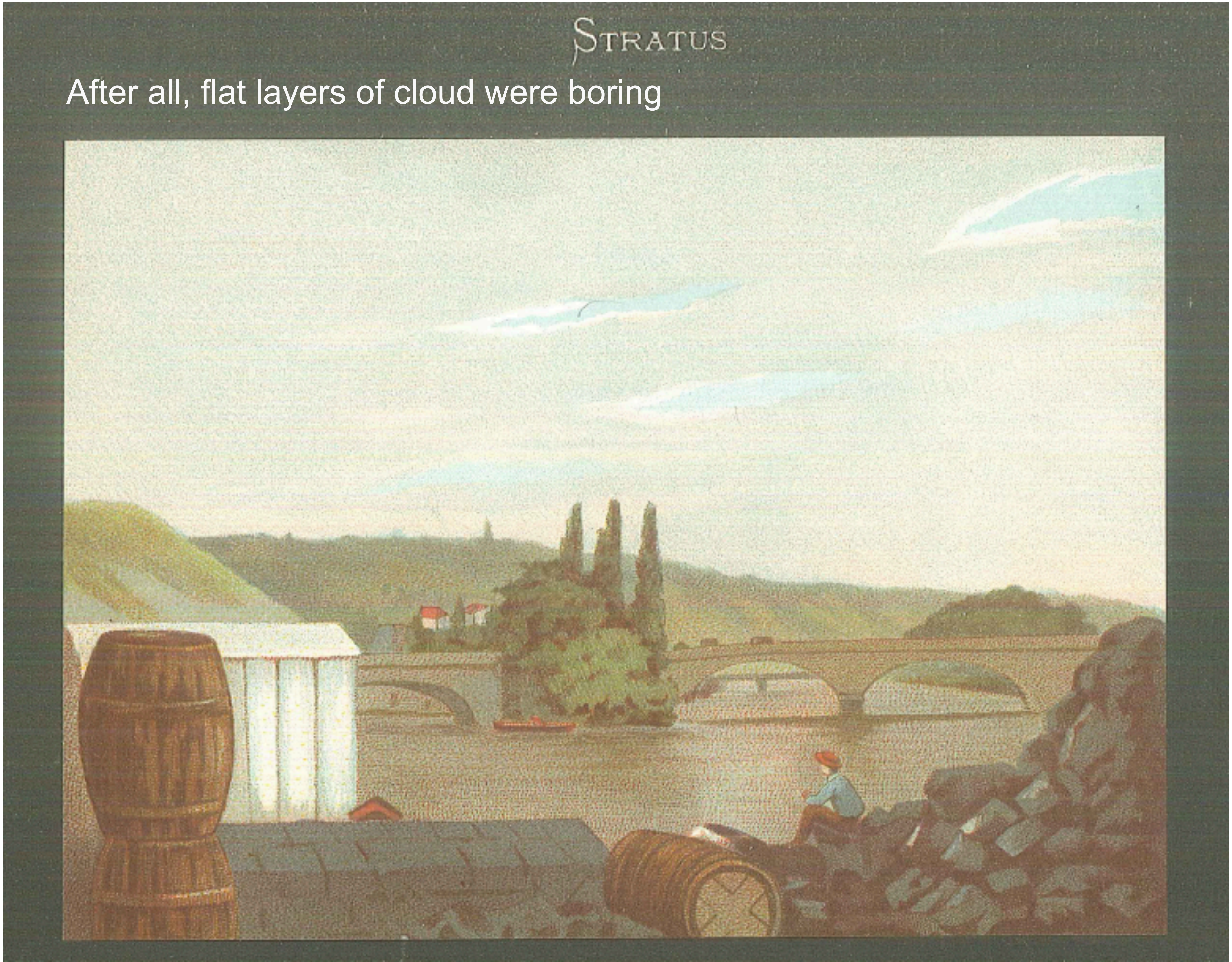


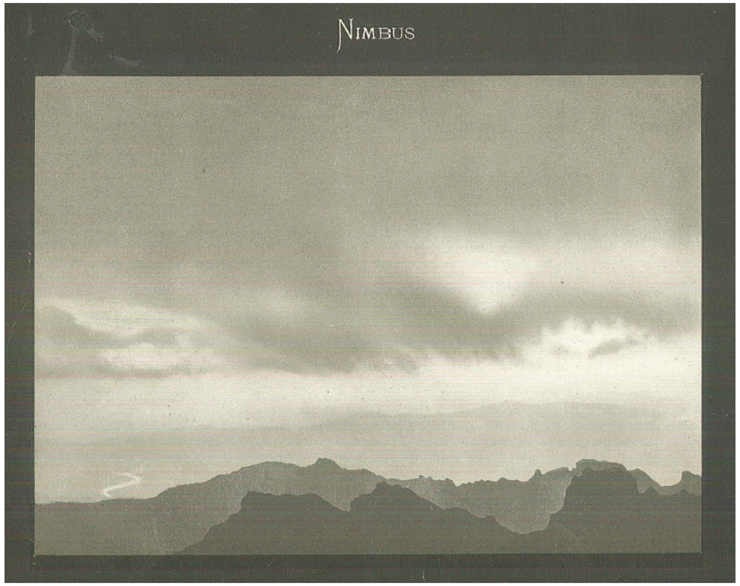
Stevens and Schwartz (2012)

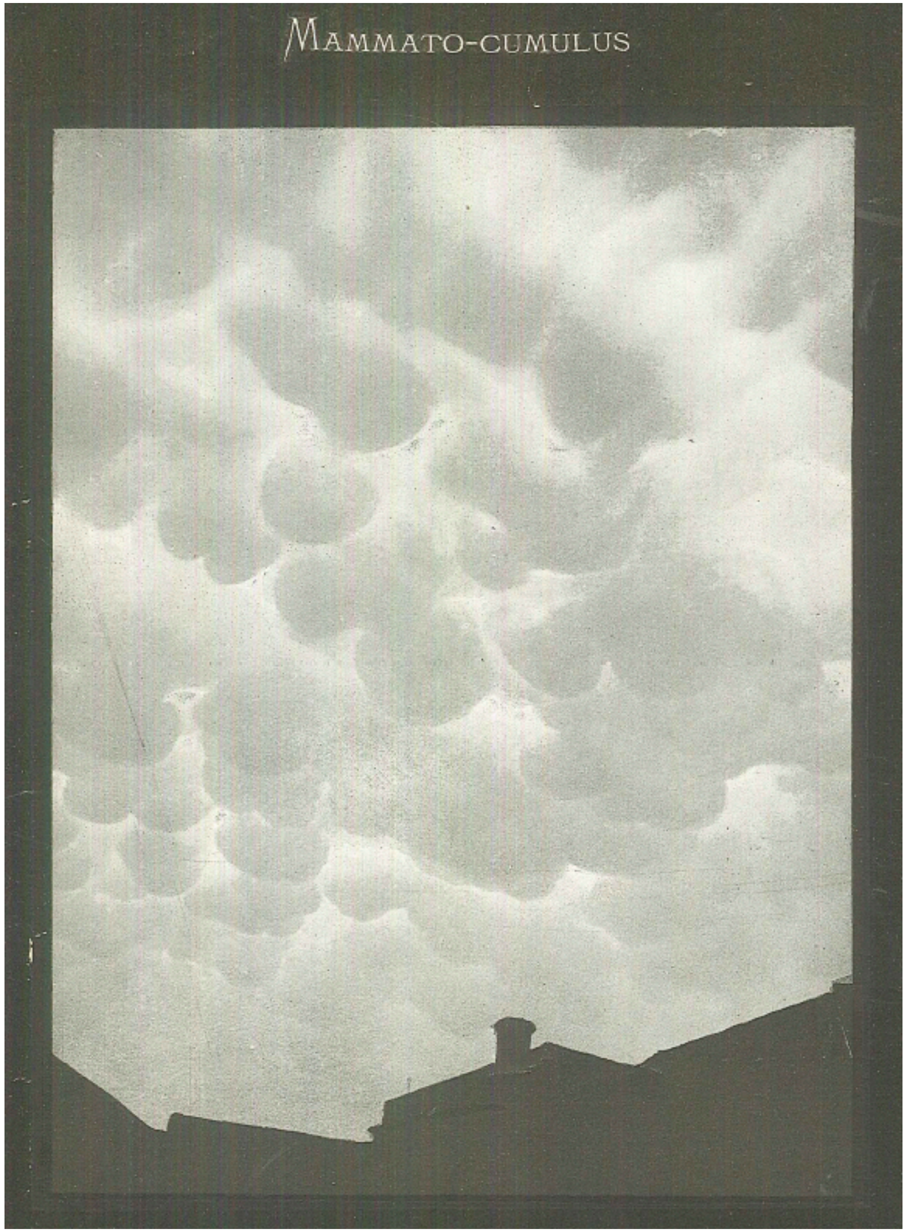
A break from cloud science?



After all, flat layers of cloud were boring







Hildebrandson (1910)

Other scientific interests drive cloud science

Abercromby:

"Understanding clouds through observing and measuring them would allow mankind to leave its fear of clouds behind, and instead conquer nature and utilize it for purposes of which poets and painters could have never dreamt of".

The desire to limit devastation and nuisance related to clouds let to:

- **Storm and weather forecasting**
- **Cloud laboratory experiments (cloud seeding and modification programs)**

Observing clouds in a similar manner around the world

I. — CLASSIFICATION OF THE CLOUDS.

The International Conference of Meteorologists held at Munich in 1891 recommended the following classification of clouds, elaborated by MM. Abercromby and Hildebrandsson :

a. Detached clouds with rounded upper outlines (most frequent in dry weather).
b. Clouds of great horizontal extent suggesting a layer or sheet (wet weather).

A. Upper Clouds, average altitude 9000^{m}.

a. 1. *Cirrus.*
b. 2. *Cirro-stratus.*

B. Intermediate Clouds, between 3000^{m} and 7000^{m}.

a. { 3. *Cirro-cumulus.*
{ 4. *Alto-cumulus.*
b. 5. *Alto-stratus.*

C. Lower Clouds, below 2000^{m}.

a. 6. *Strato-cumulus.*
b. 7. *Nimbus.*

D. Clouds of diurnal ascending currents.

a. 8. *Cumulus;* top 1800^{m}; base 1400^{m}.
b. 9. *Cumulo-nimbus;* top 3000^{m} to 8000^{m}; base 1400^{m}.

E. High Fogs, under 1000^{m}.

10. *Stratus.*

III. — INSTRUCTIONS FOR THE OBSERVATION OF CLOUDS.

The observer should first of all determine whether he is dealing with an *Upper Cloud*, an *Intermediate Cloud* or a *Lower Cloud*, or with a variation of the *Cumulus* or the *Stratus* type.

Having done so, he should assign the cloud to one or other of the forms included in these general groups. It must not be forgotten that *typical forms are relatively rare;* as a general rule we meet with forms which are intermediate between the typical forms. In every case the typical form which the cloud observed most nearly resembles should be noted in the register. Thus the first thing to do is to decide upon *the group to which the observed cloud belongs*. Then after consulting the definitions and plates given herewith we proceed to note which *typical form* the cloud under observation most nearly resembles.

In each observation the following points should be noted and entered in the register or schedule :

1. **The kind of cloud,** indicated by the international abbreviations of the name of the cloud, as given above.

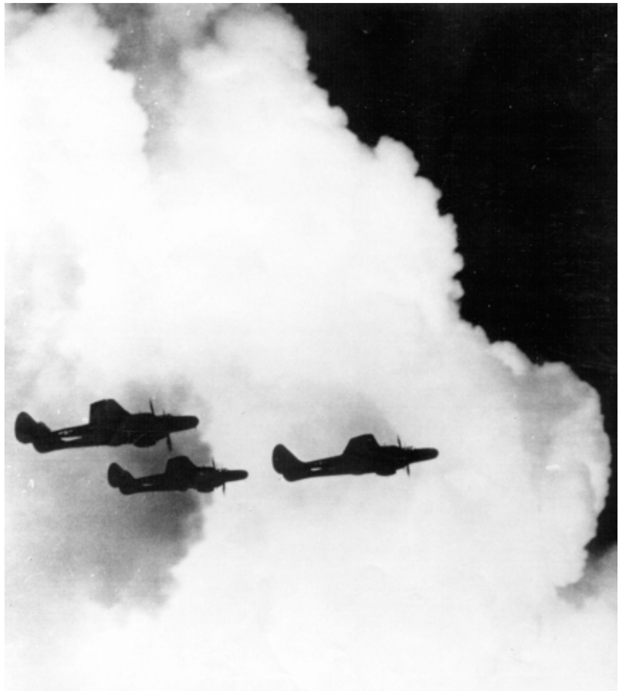
2. **The direction from which the cloud comes.** — By remaining perfectly still for several seconds, the motion of clouds may be observed easily

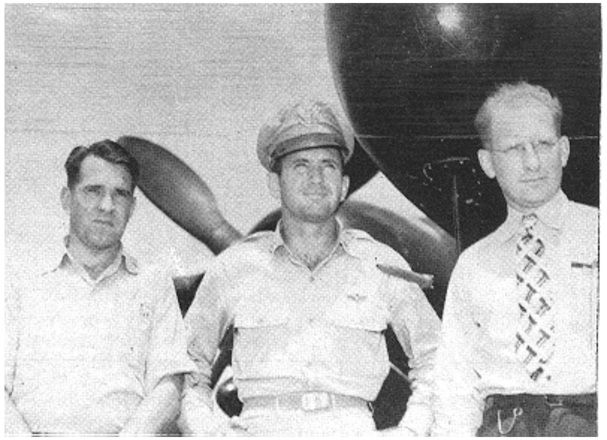
d. A note should always be made of the fact when the clouds seem to be stationary or in very rapid motion.

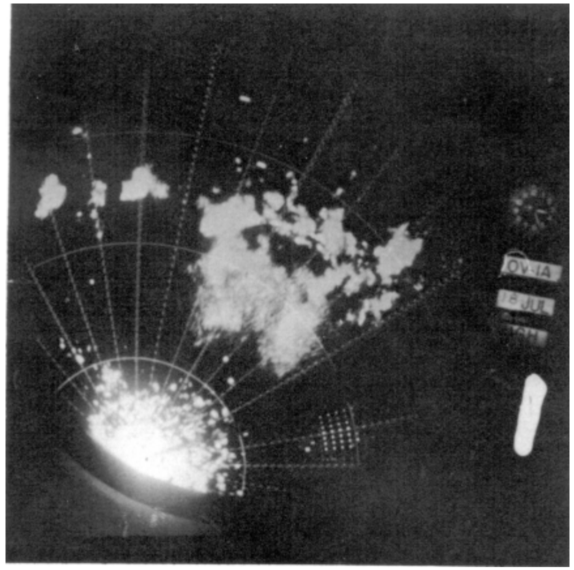
Hildebrandson (1910)

Severe storm research

The Thunderstorm Project
1363 penetrations through thunderstorms at various altitudes without an accident



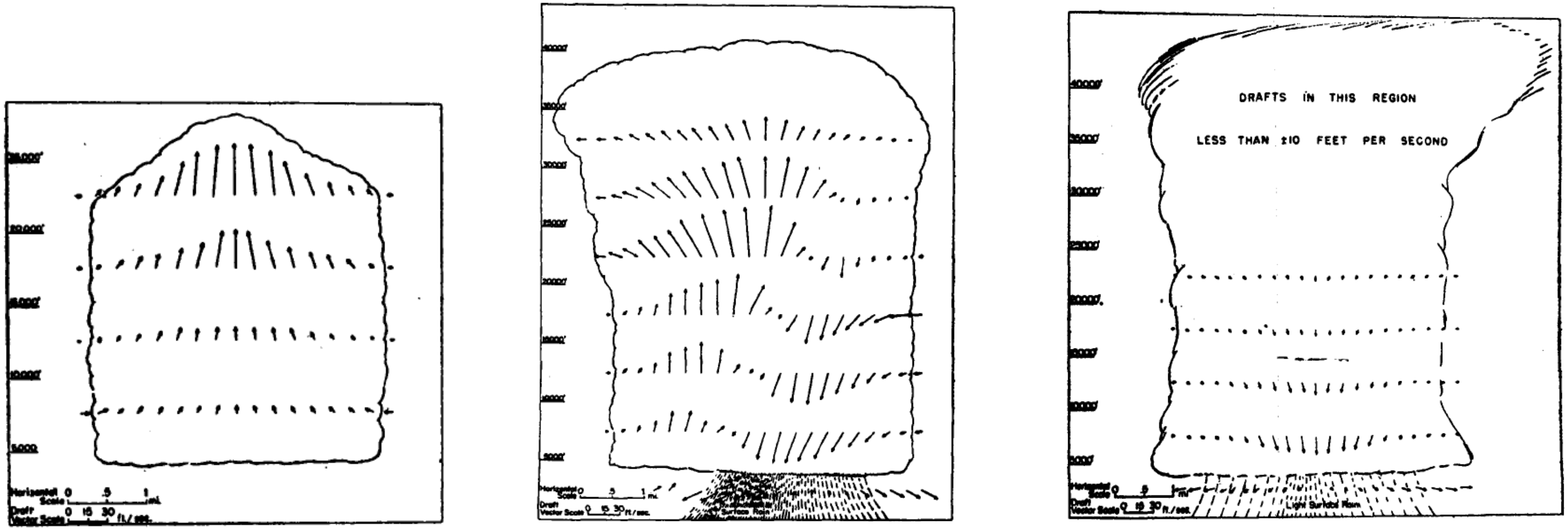




Photographs courtesy by NOAA

Severe storm research

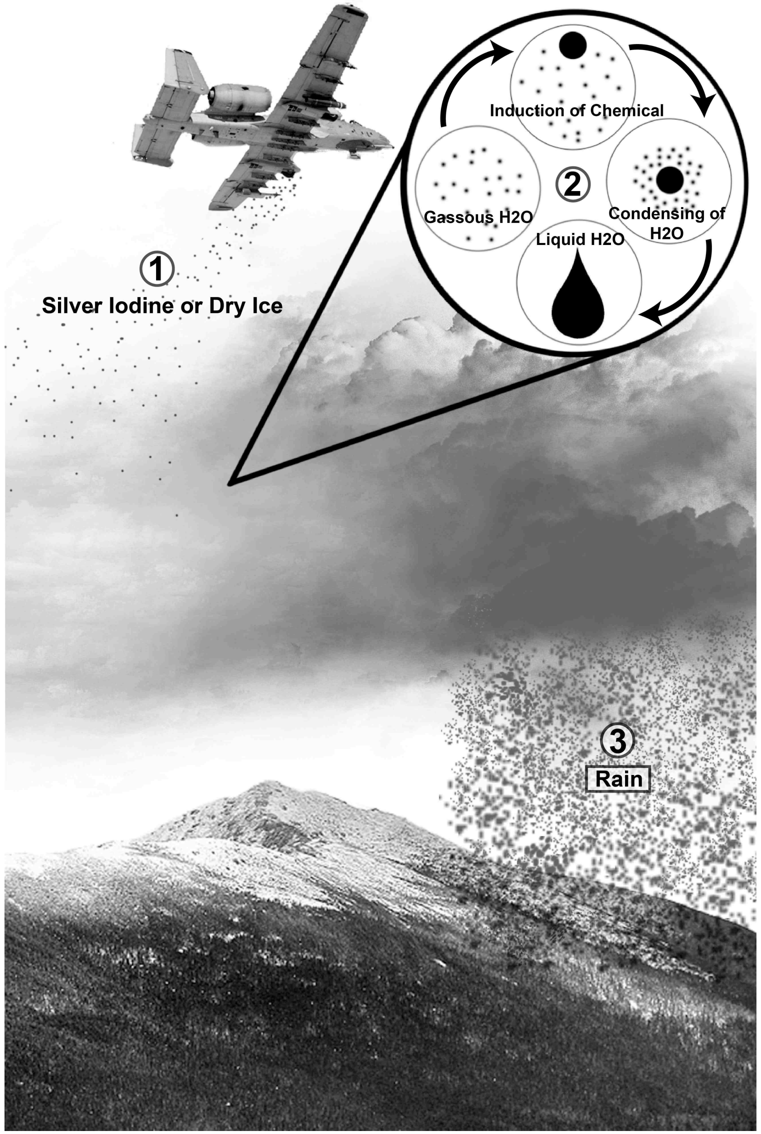
1. three stages in the life cycle of cumulus
2. ascending air cools at a rate faster than wet adiabatic
3. areas of stormy turbulence are surrounded by a narrow belt of smooth cloud-filled air

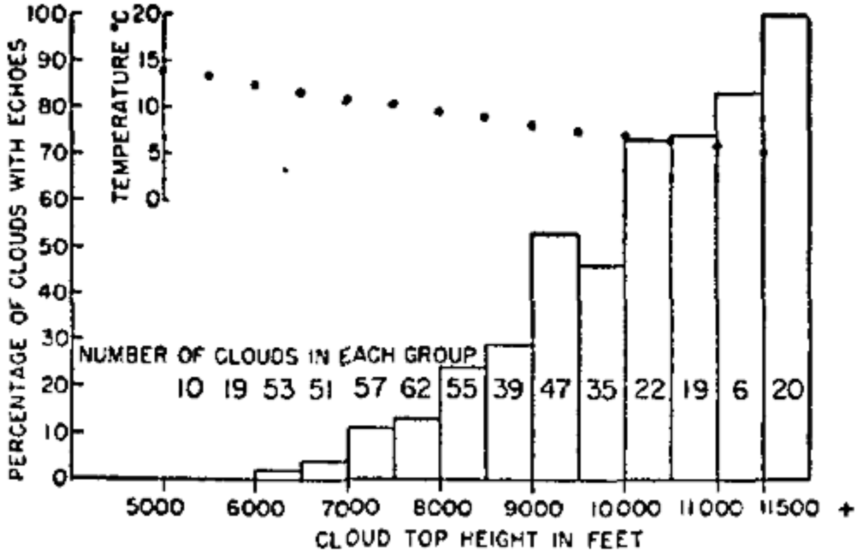


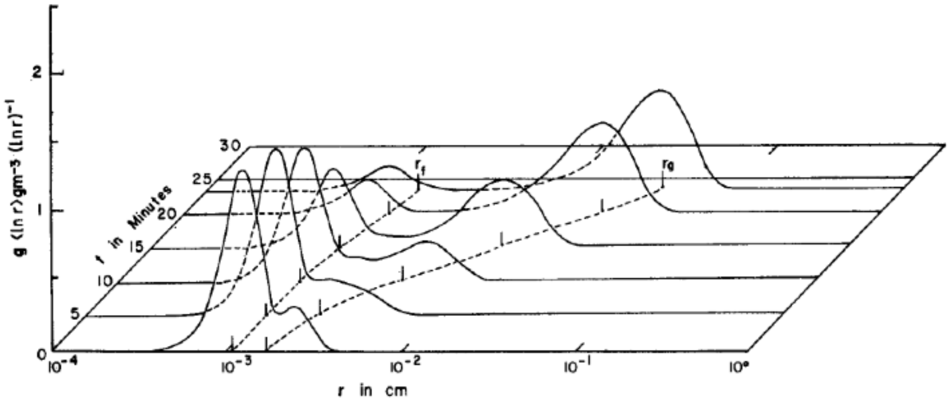
“One may say that heretofore meteorologists, in emphasizing the thunderstorm updraft, have been barking up the wrong tree. The downdraft is by far the most striking feature, at least in the levels at or near the ground.”

Byers (1949)

Making rain







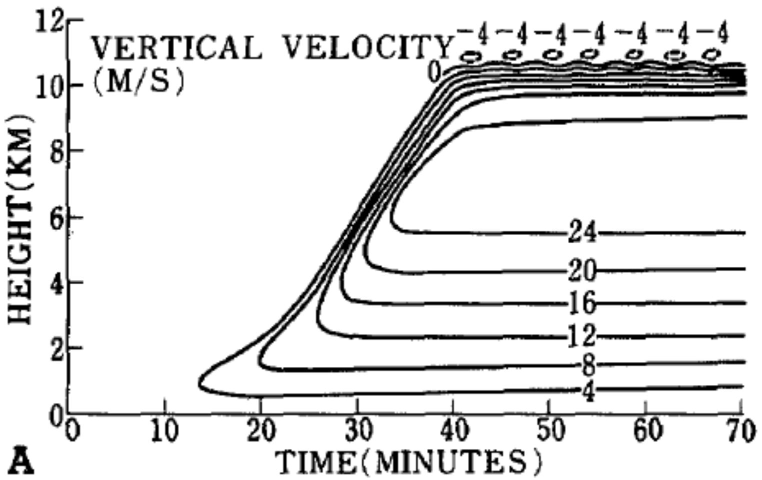
Heywood (1940), Byers and Hall (1954), Berry and Reinhard (1974)

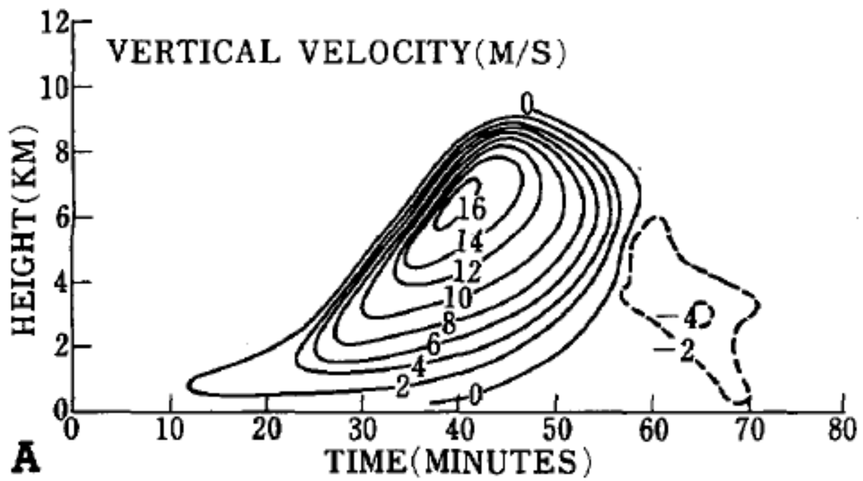
The first parameterizations

Kessler's funded project in the US ('63): "The purpose of the project is to increase understanding of the roles of cloud conversion, accretion, evaporation and entrainment processes in shaping the distributions of water vapor, cloud, and precipitation associated with **tropical** circulations"

Mason: "Microphysical research is irrelevant to natural problems when disregarding the dynamics of the flow"

Ogura and Takahashi: "The growth and fallout of precipitation interact with the updraft, which in turn controls the amount and development of hydrometeors, and latent heating"

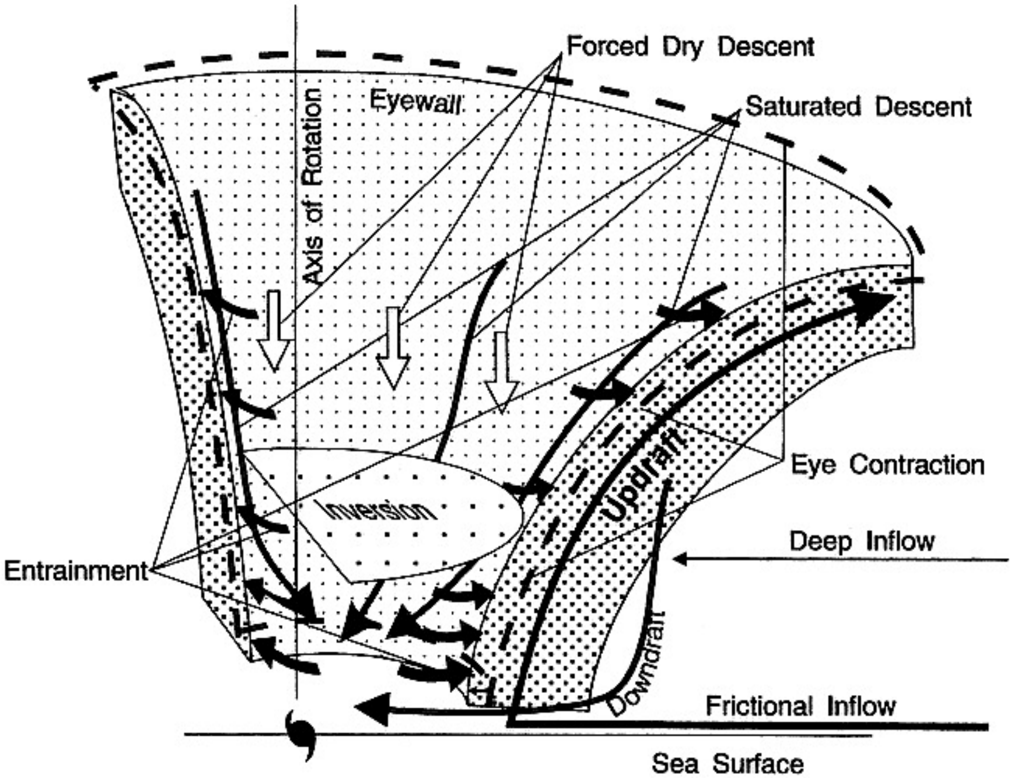


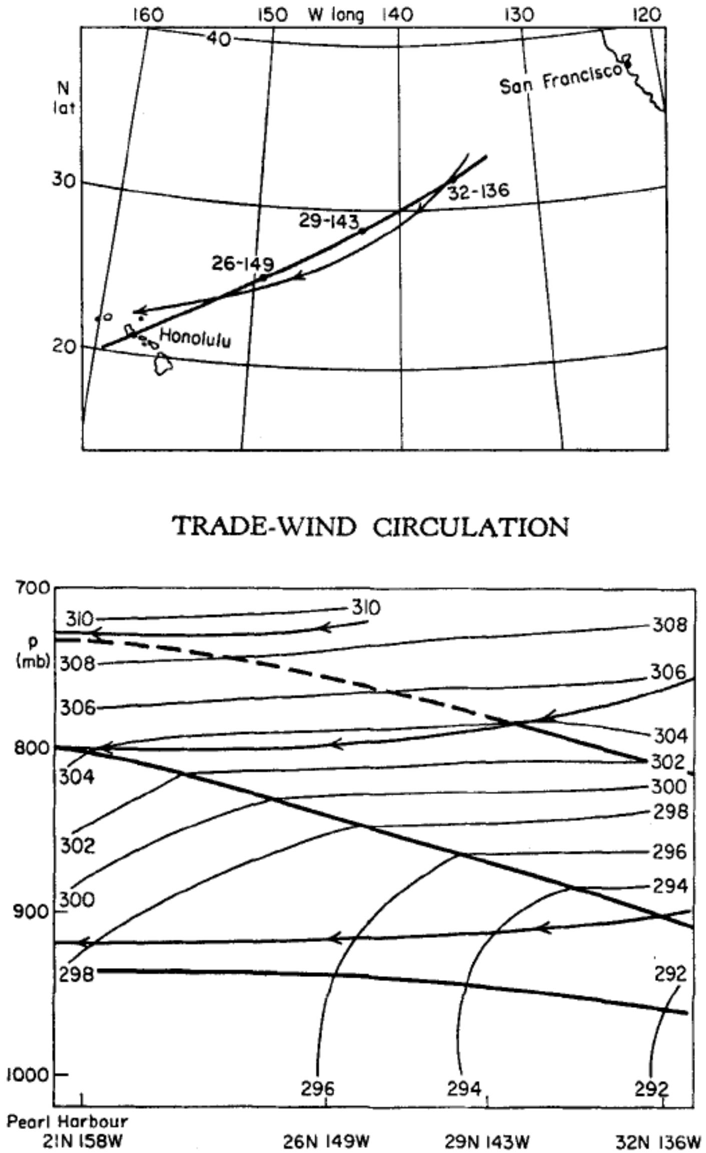


Max-Planck-Institut
für Meteorologie

Kessler (1963,1994), Mason (1969), Ogura and Takahashi (1971)

Role of clouds as buoyant hot towers

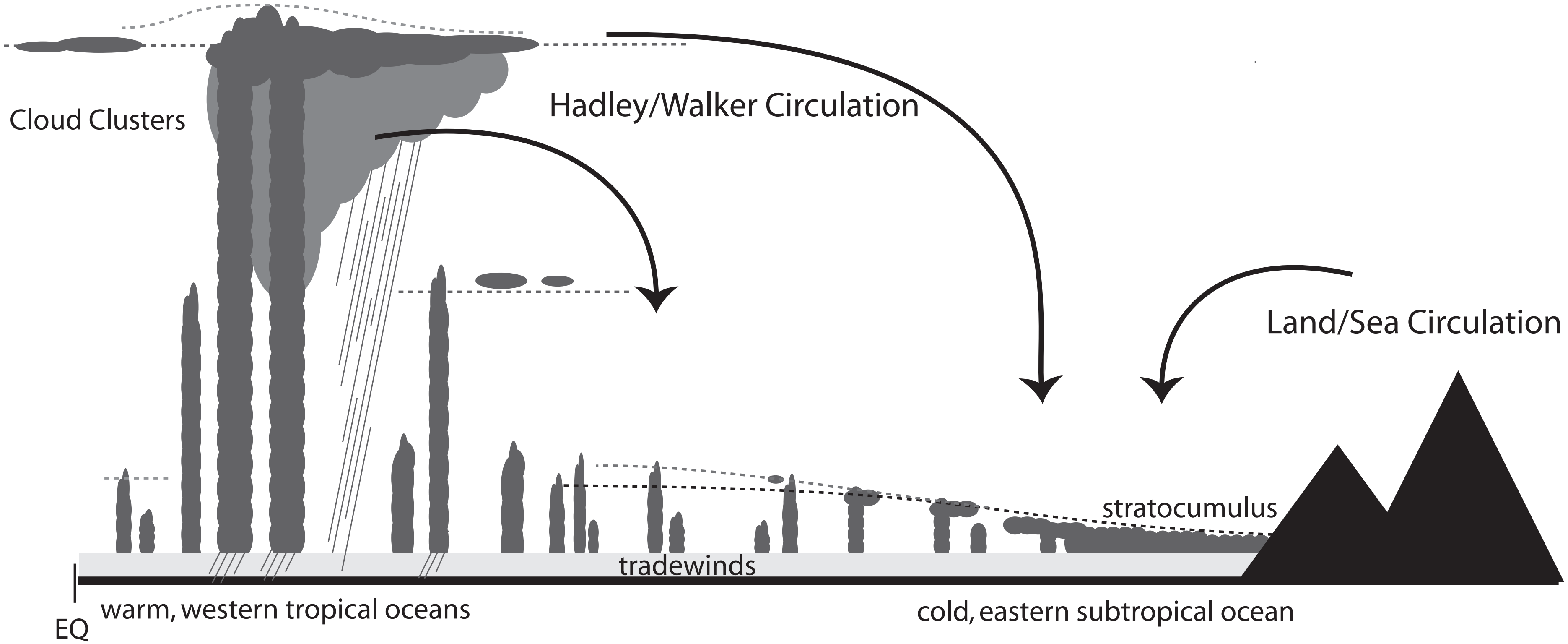




Moist adiabatic ascent in hurricane eyewalls takes place in regions of buoyant hot towers, that entrain air and force dry ascent in the eye.

Riehl and Malkus (1956), Malkus and Riehl (1960), Willoughby (1998)

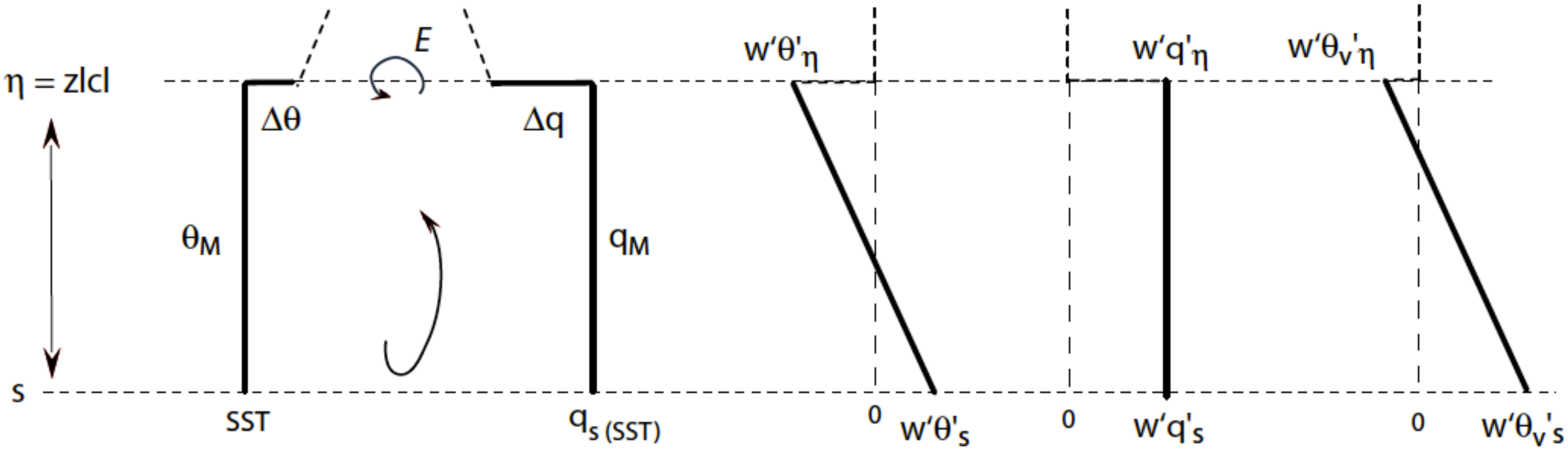
The large-scale circulation



Clouds are not just visual expressions of the state of the atmosphere, or a collection of small droplets that produce considerable rainfall, rather, they are a crucial component of the dynamics of the atmosphere as a whole

Stevens (2005), after Arakawa (1975)

Theoretical models of boundary layer clouds



The vertical structure of the boundary layer can be represented by one or two idealized (bulk/ slab) layers. For each layer the prognostic equations of thermodynamic quantities are integrated, or vertically averaged, over the depth of that layer:

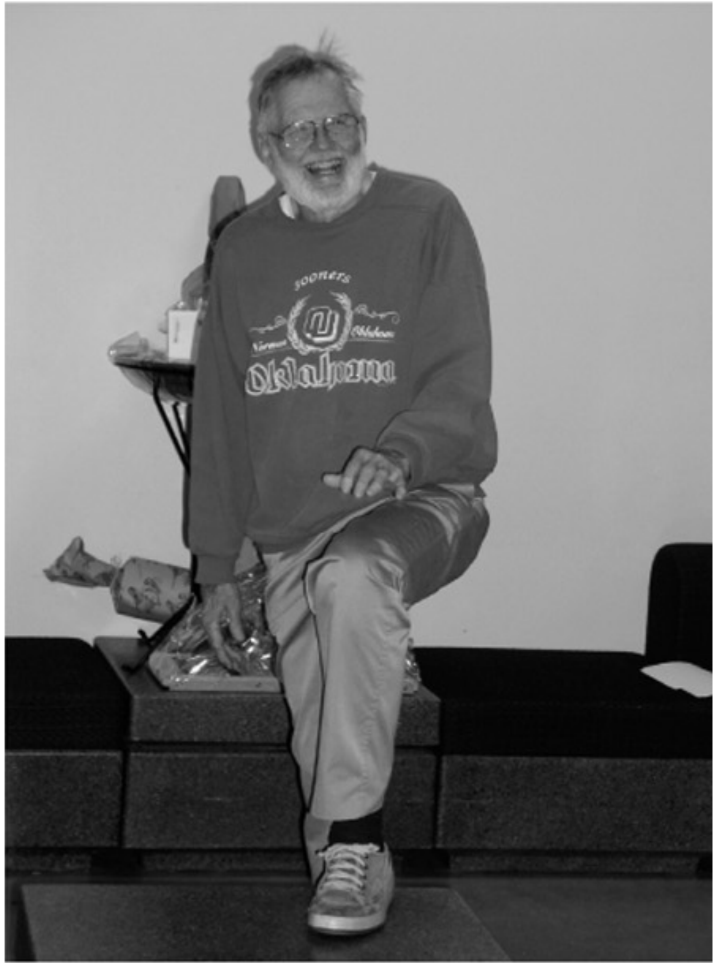
$$\langle \phi \rangle = \frac{1}{\eta} \int_s^\eta \phi \, dz$$

Doug Lilly’s mixed layer model

“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.

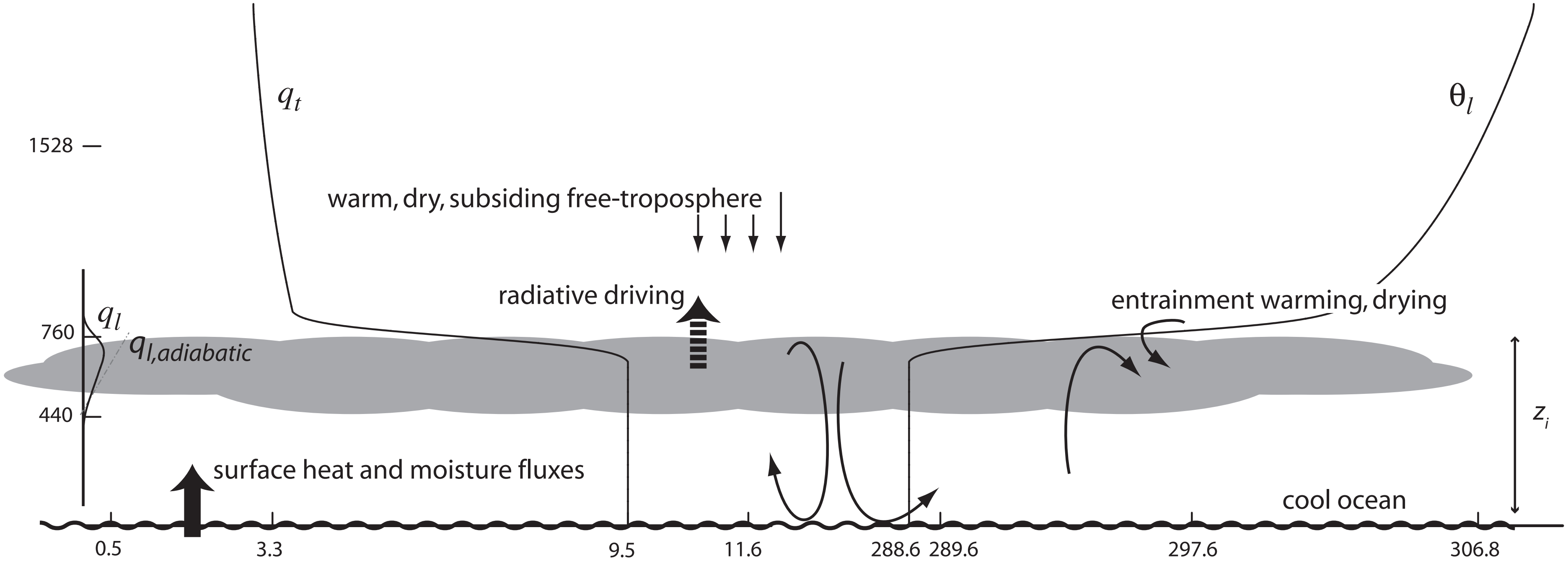
The phenomenon considered here (cloud top mixed layers) represents one form, in some respects a relatively simple one, of this interaction. There is considerable lack of highly definitive observational data on layered convection; in fact on most kinds of non-violent cloud convection.

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.”



Lilly (1968), picture from a biography in the book by Fedorovich et al (2004)

Stratocumulus



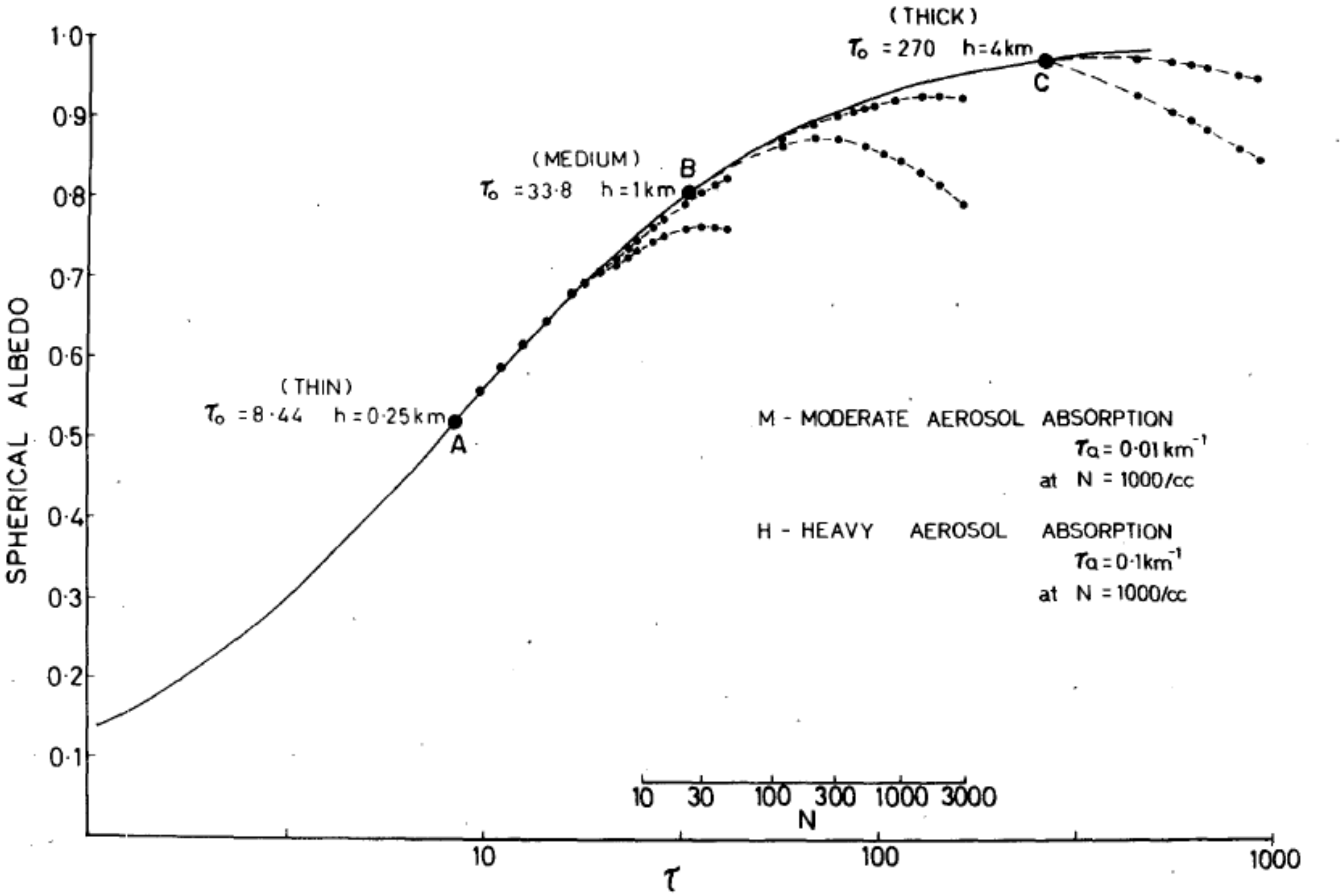
Radiative cooling at the top drives turbulence

Unlike deep convection: SW heating and LW cooling effects do not cancel

Large decks of stratocumulus particularly interesting to studies questioning aerosol effects on cloud albedo

Stevens (2005)

Dirty clouds



Twomey (1977)

Clouds as a feedback mechanism?

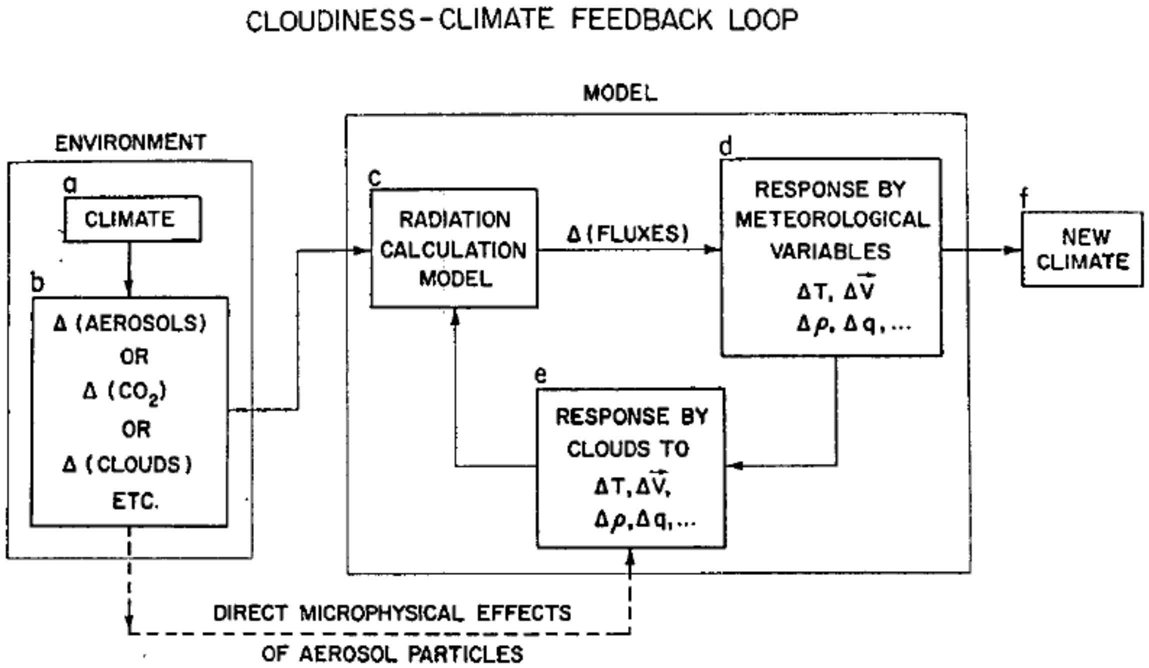


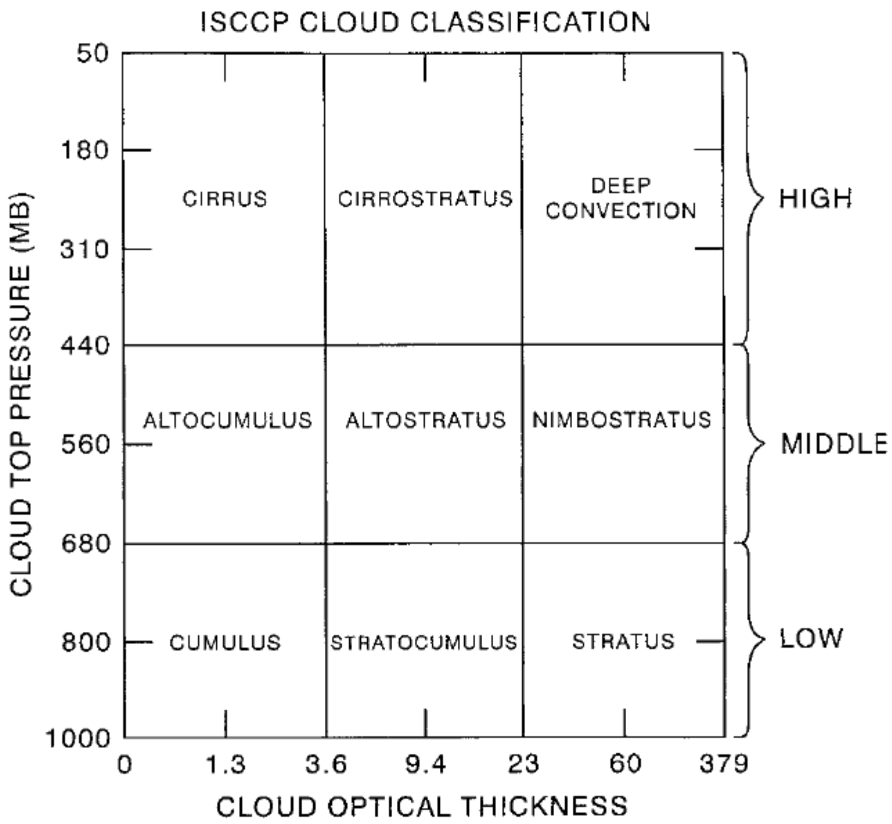
FIG. 1. Flow chart illustrating the possible role of cloudiness as a climatic feedback mechanism. The arrows represent the order in which calculations would be made by a climate model attempting to predict the effect of changes in environment (e.g., $\Delta(CO_2)$ on the climate).

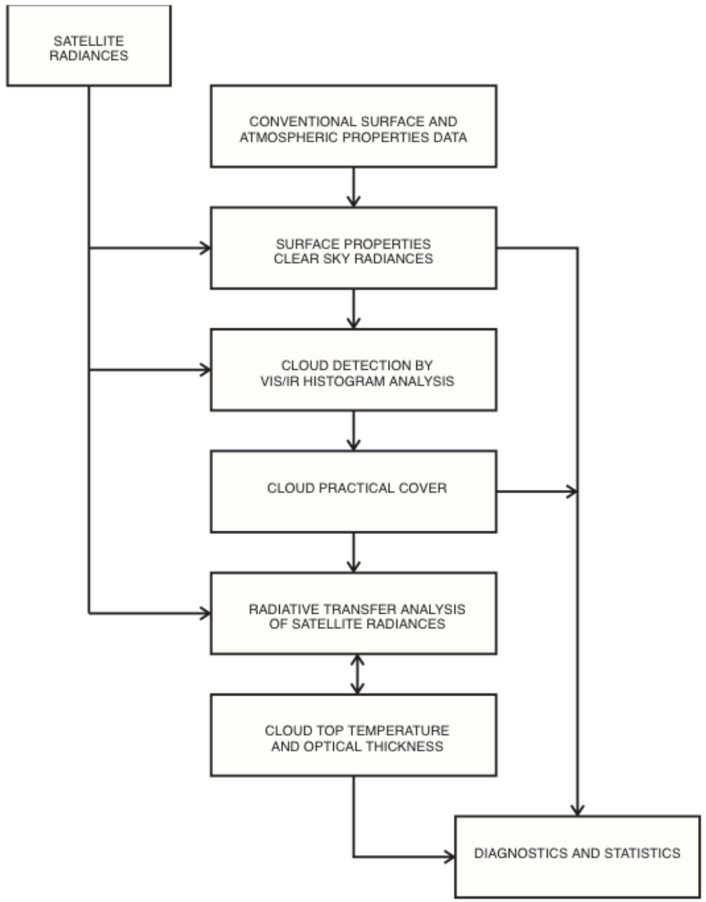
"In order to understand the possible role of cloudiness as a global climate feedback mechanism, it is necessary to have a realistic, large-scale, radiative and dynamical model of the land-atmosphere-ocean system, that includes some microphysical aspects of cloud formation"

Schneider (1978)

International Satellite Cloud Climatology Project (WCRP / 1982)

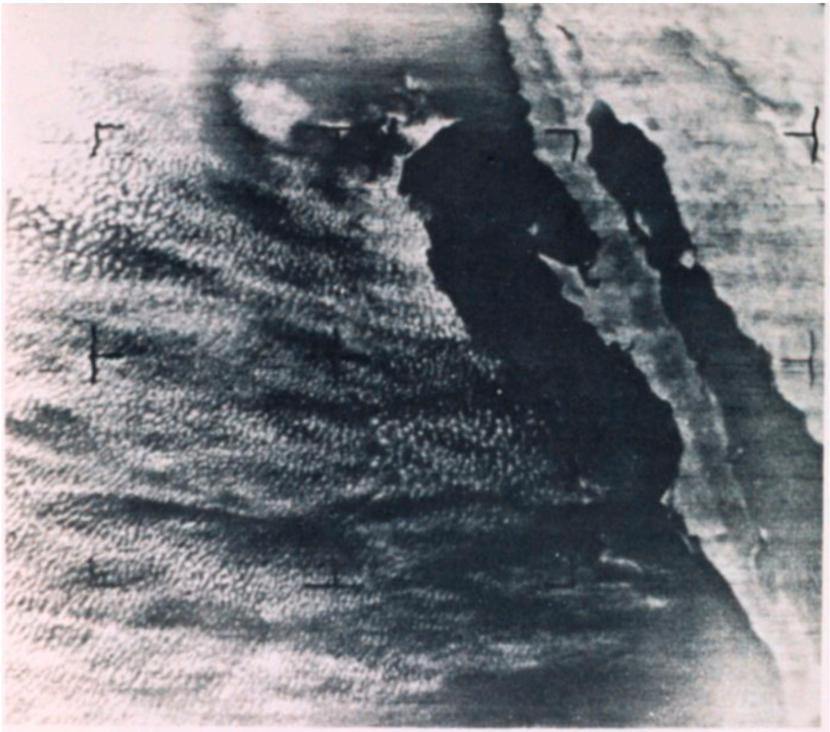
Past cloud climatologies did not contain sufficient information on cloud-top temperature (or altitude) or on the optical properties of clouds required by climate modelers to calculate the first-order effects of clouds on the earth's radiation budget or the climate feedbacks produced by cloud





Schiffer and Rossow (1983)

Visible satellite imagery



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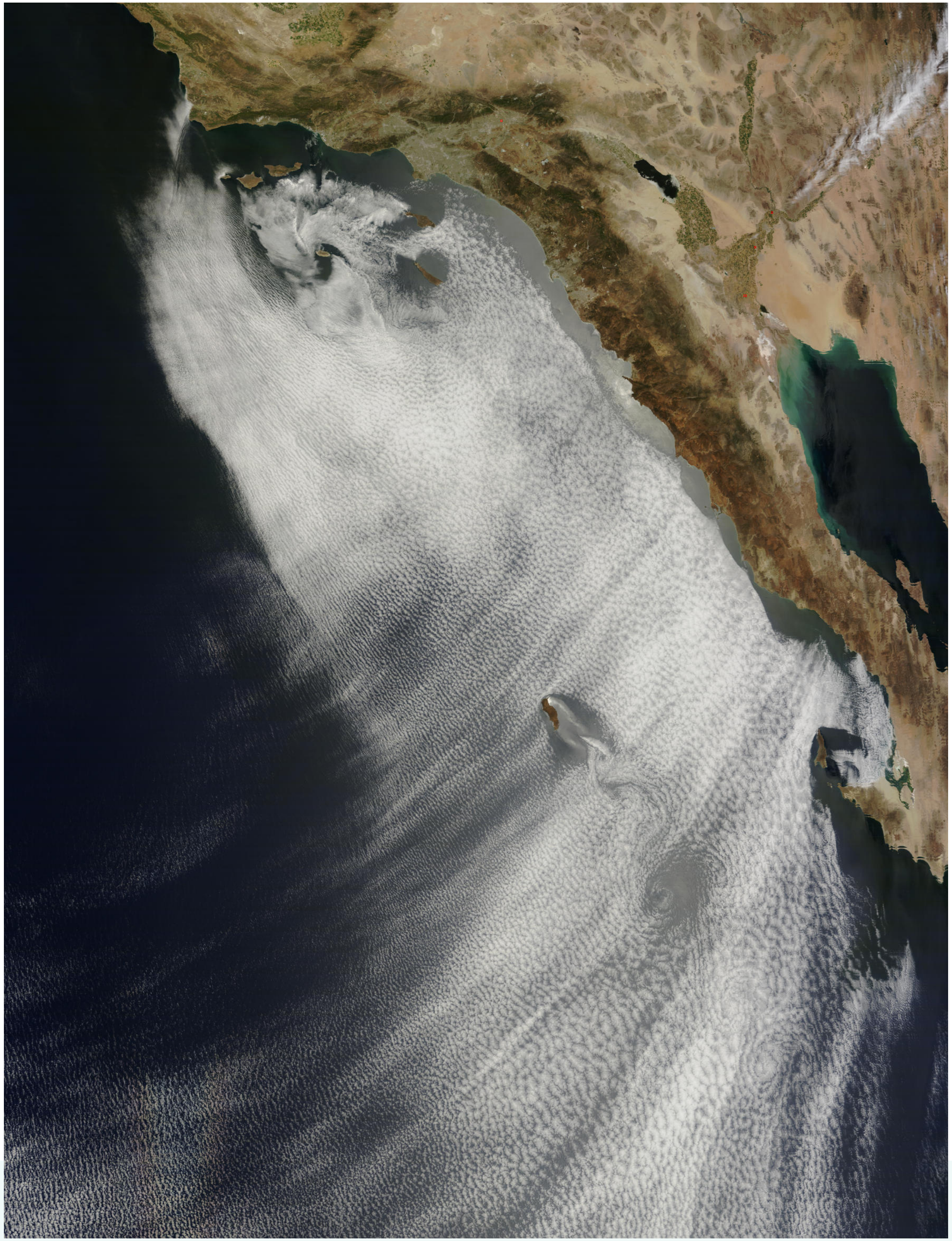
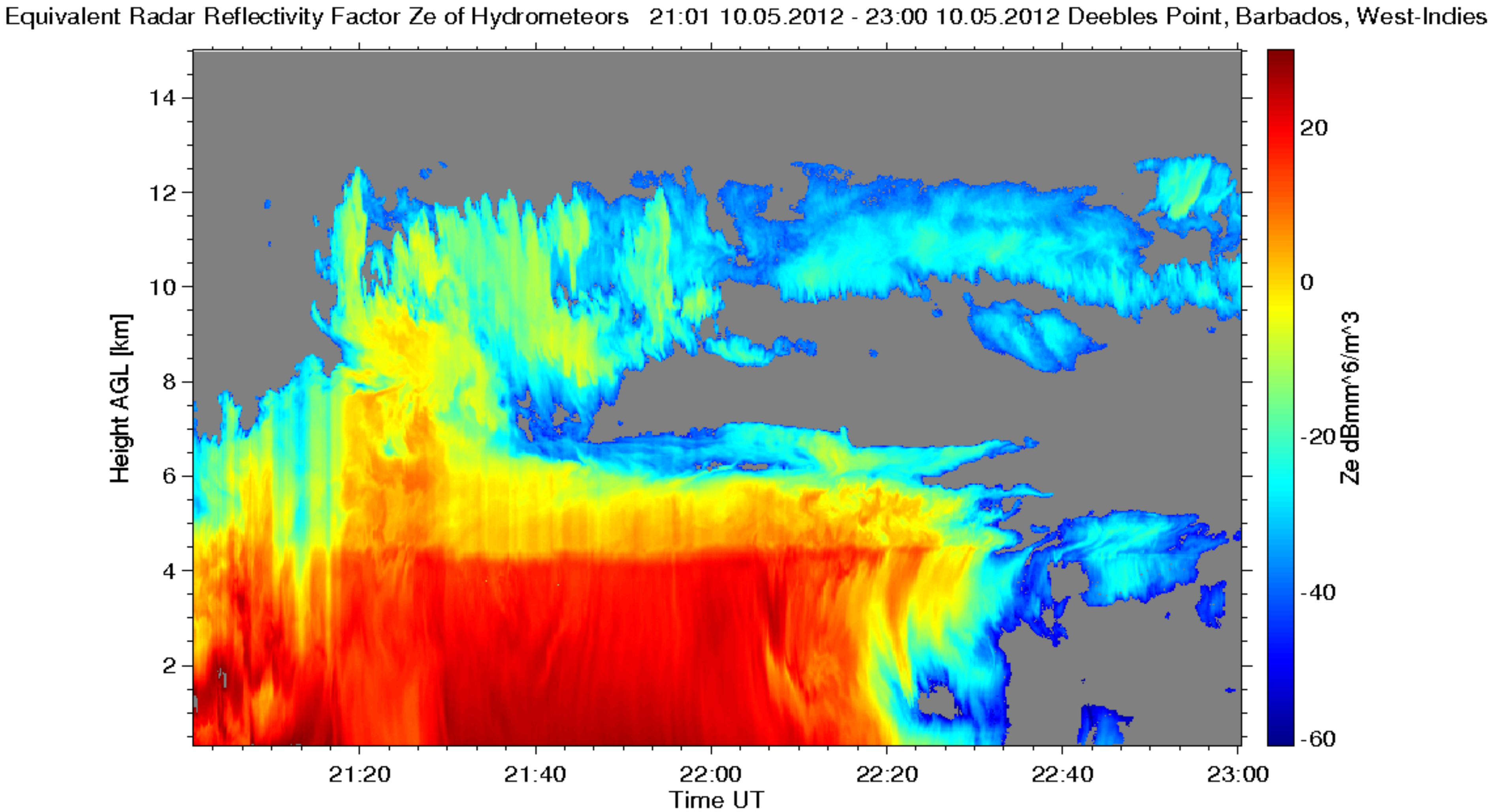
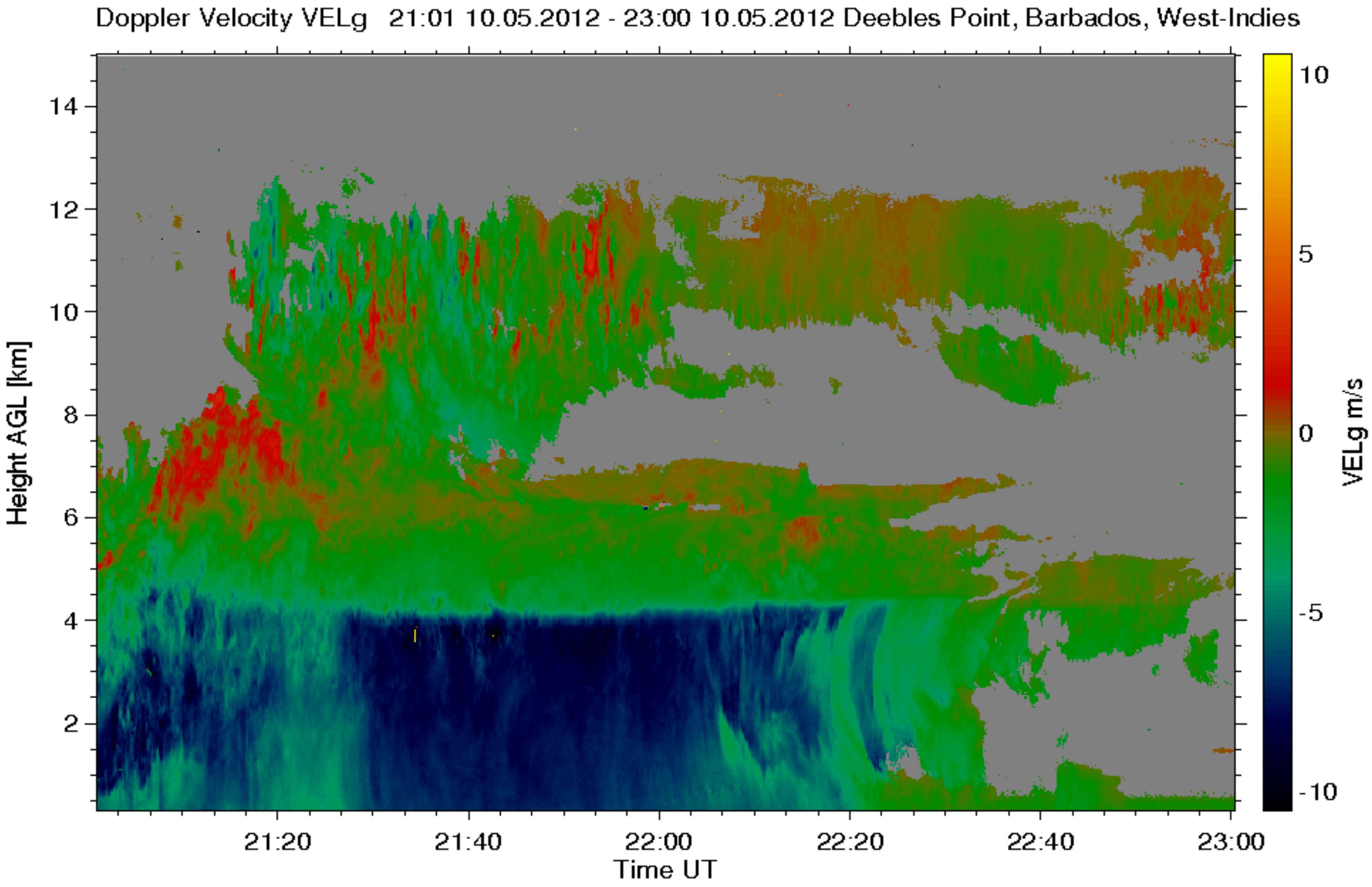


Doppler radar



Doppler radar



After an era of intensive cloud studies driven by various scientific interests, we have:

A good theoretical understanding of the processes that govern clouds - whether microphysical, turbulent, radiative or dynamical processes

A hierarchy of model and simulation tools to study clouds on a variety of scales

State-of the art satellite and ground-based observation platforms

International programs that combine our efforts

We have a reasonably good idea of the impact of clouds on our current climate

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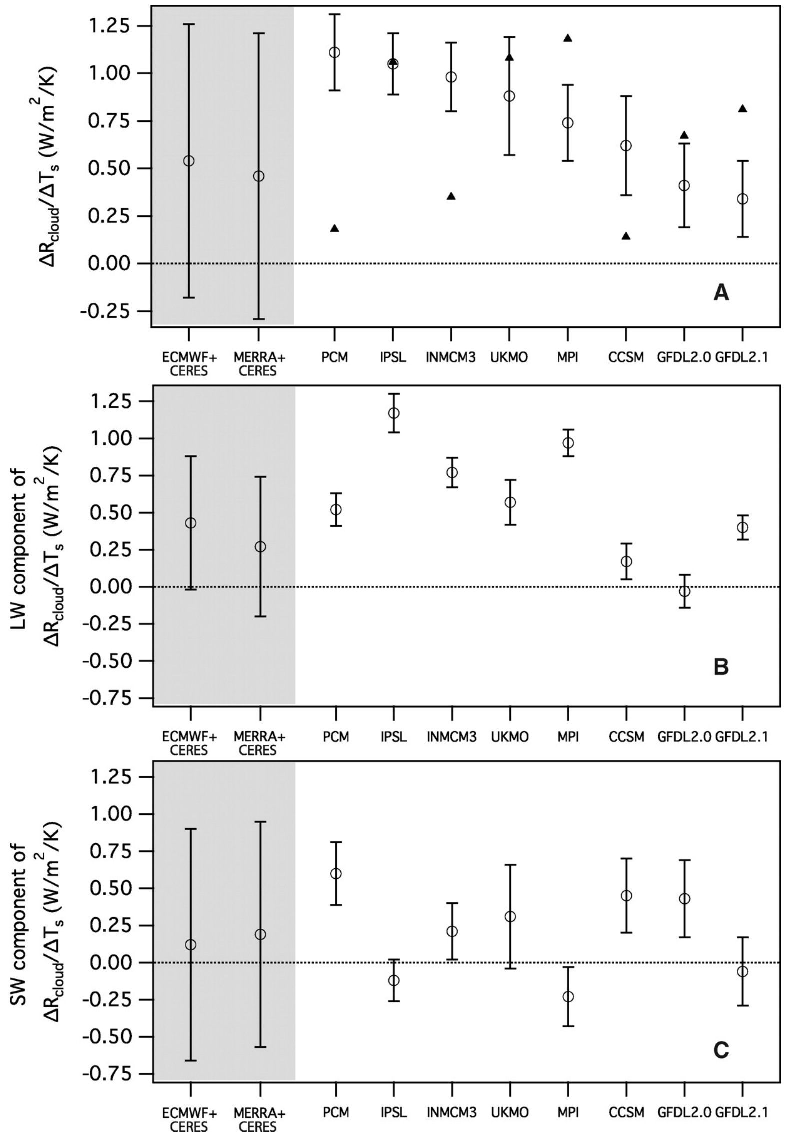
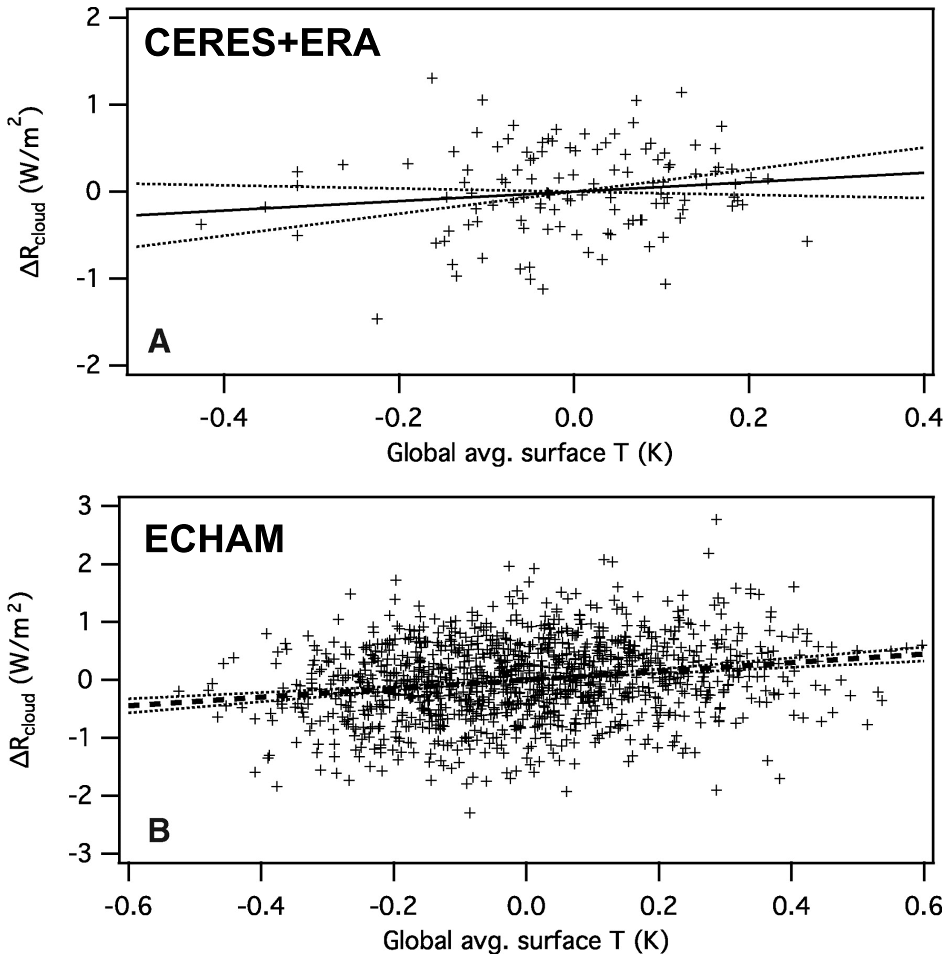
We have a reasonably good idea of the impact of clouds on our current climate

How do clouds change with changes in global mean sea surface temperature?

How do such changes alter the sensitivity of our climate to perturbations?

Positive cloud feedback in observations and climate models





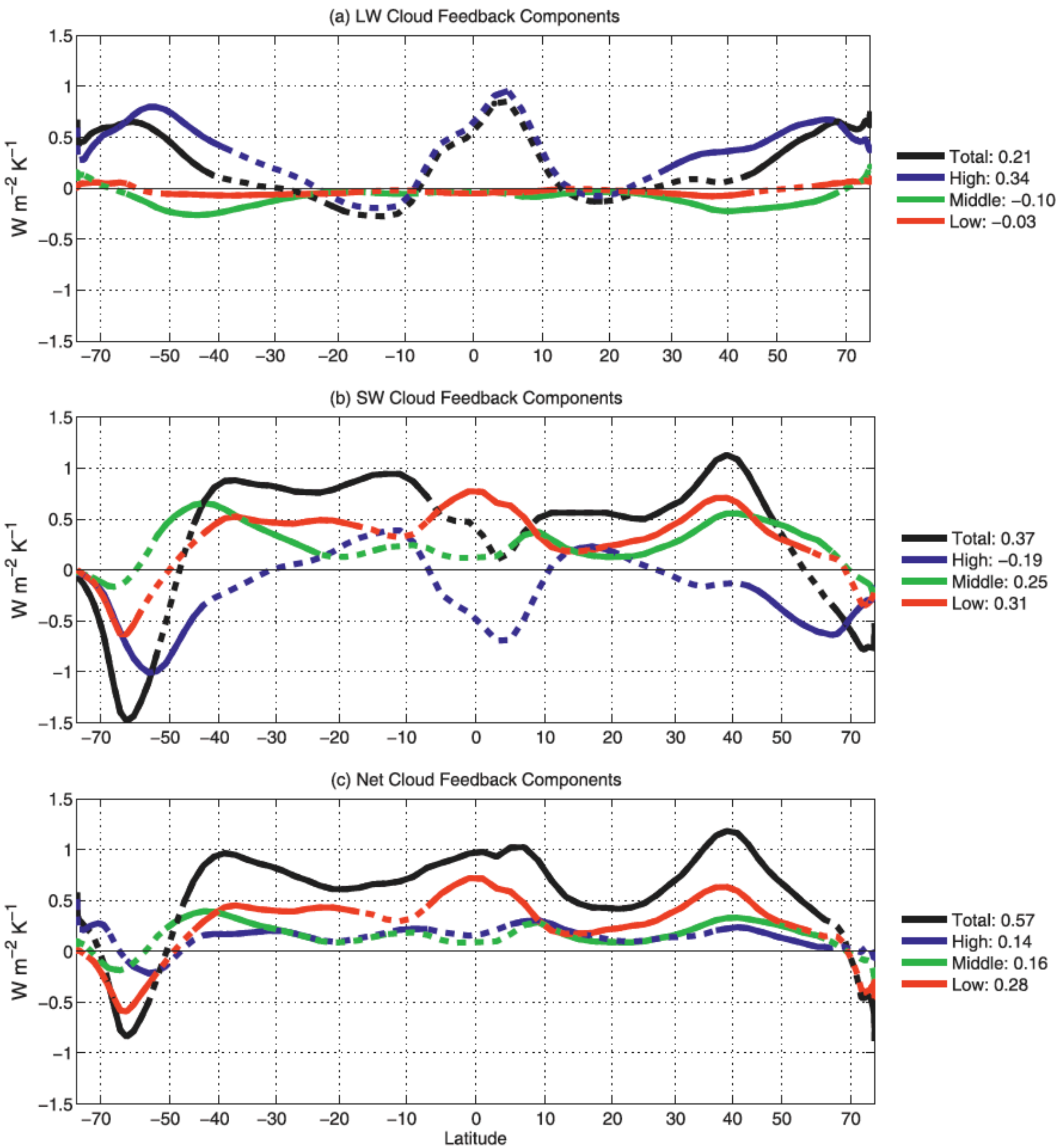
Dessler (2010)

Cloud feedbacks by cloud type

LW

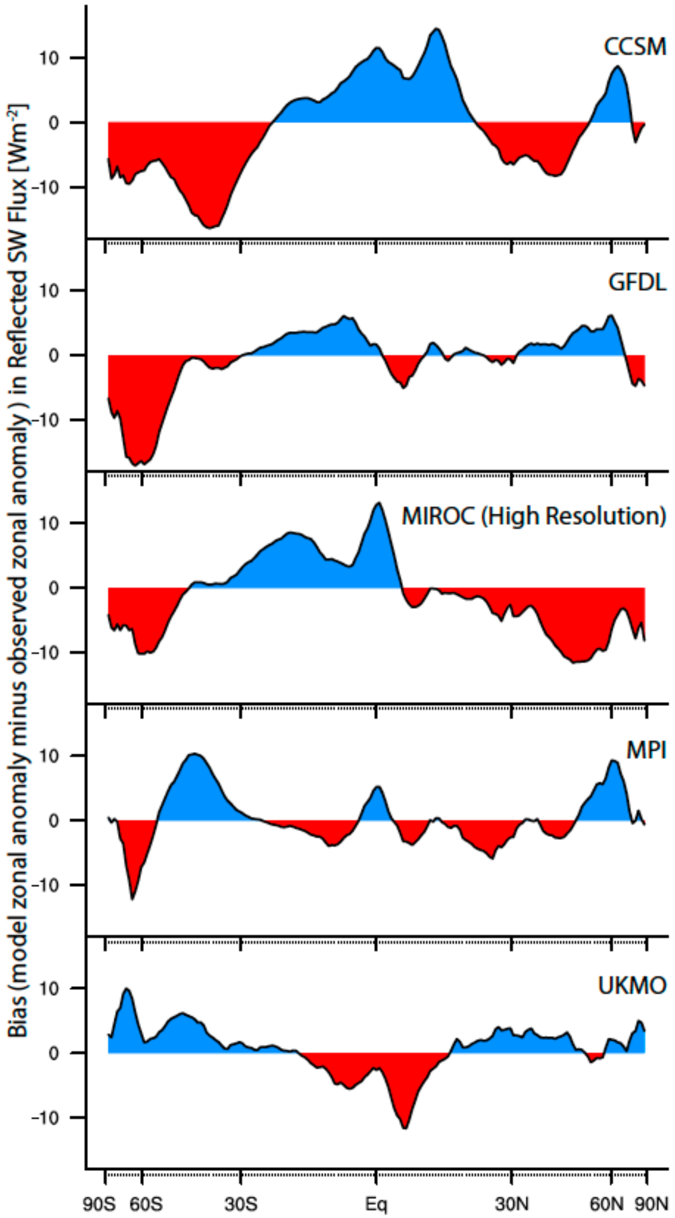
SW

Net



Zelinka et al (2012)

Biases in reflected shortwave radiation

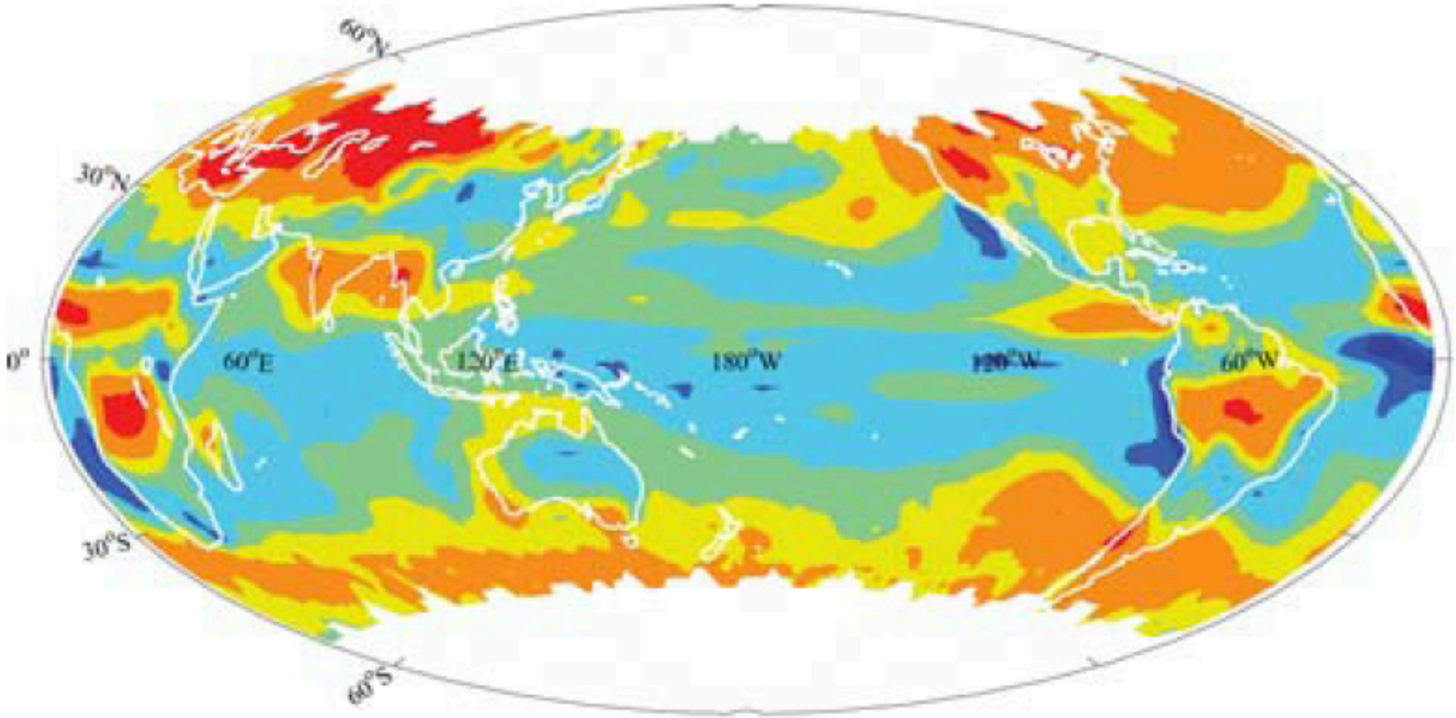


blue = too little absorption in the model

red = too much absorption in the model

Stevens and Schwartz (2012)

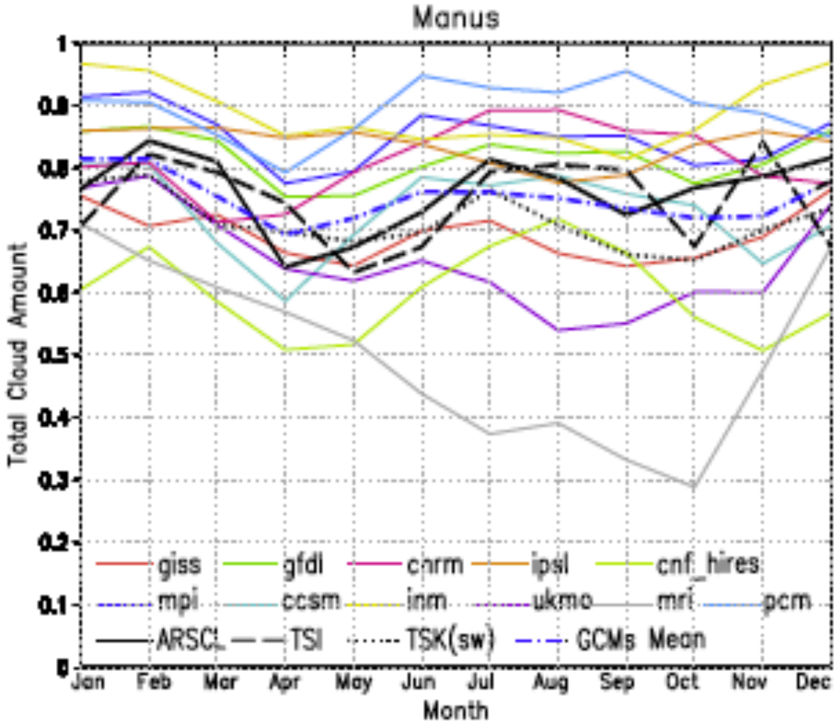
Yet our models poorly reproduce variability in e.g. the planetary albedo



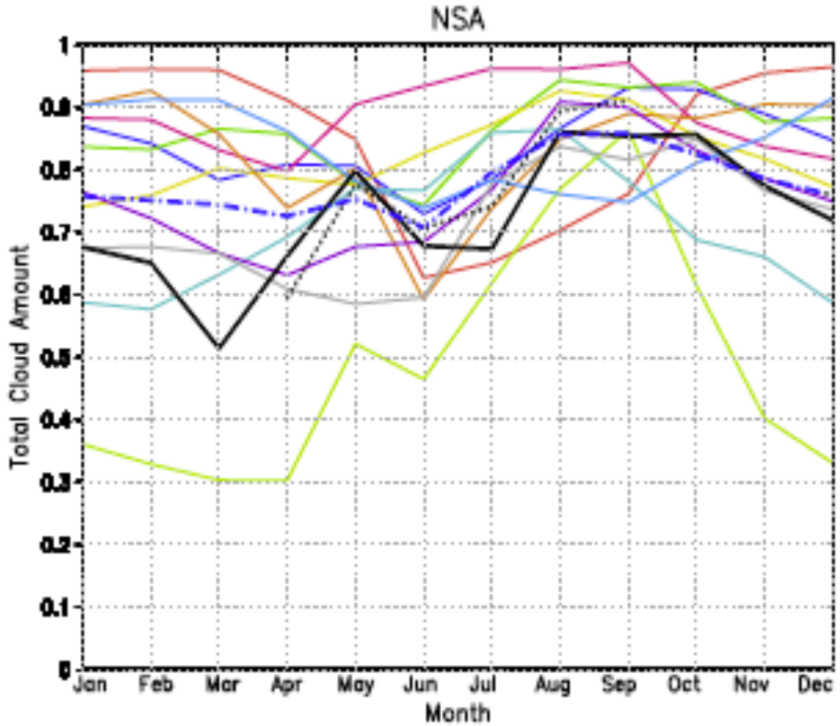
Correlation between albedo from ERBE and climate models

Bender et al (2006)

Biases in seasonality cloud amount

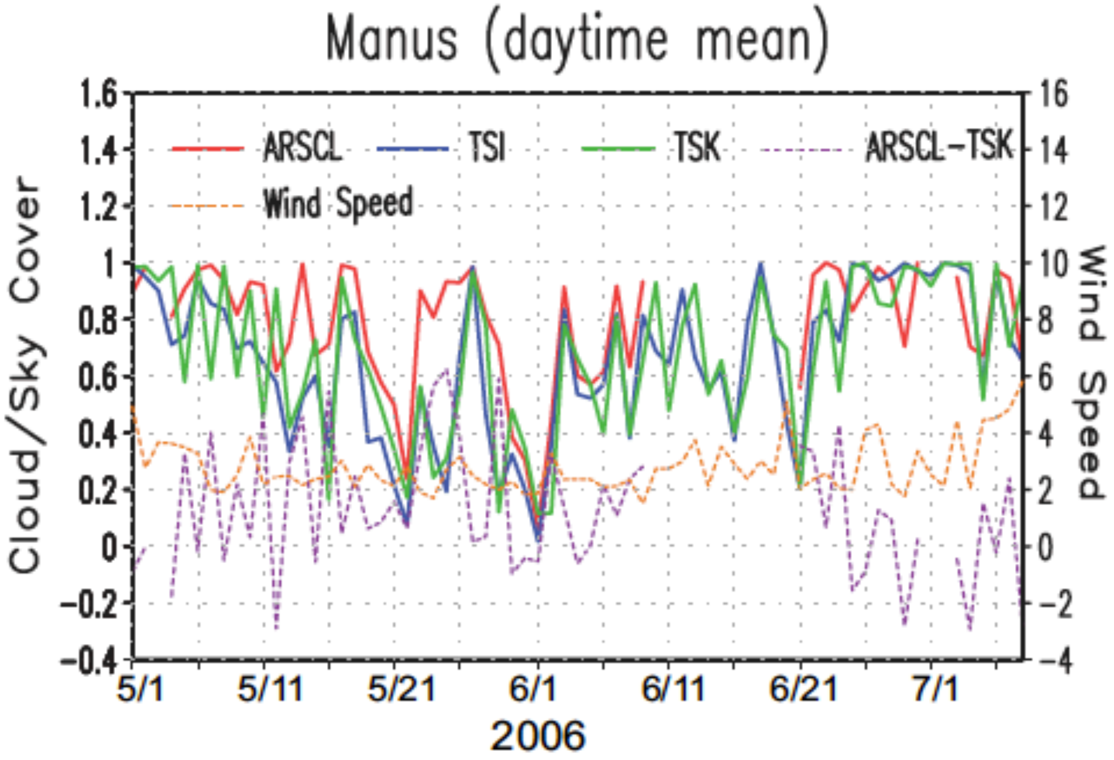


Manus, Papua New Guinea



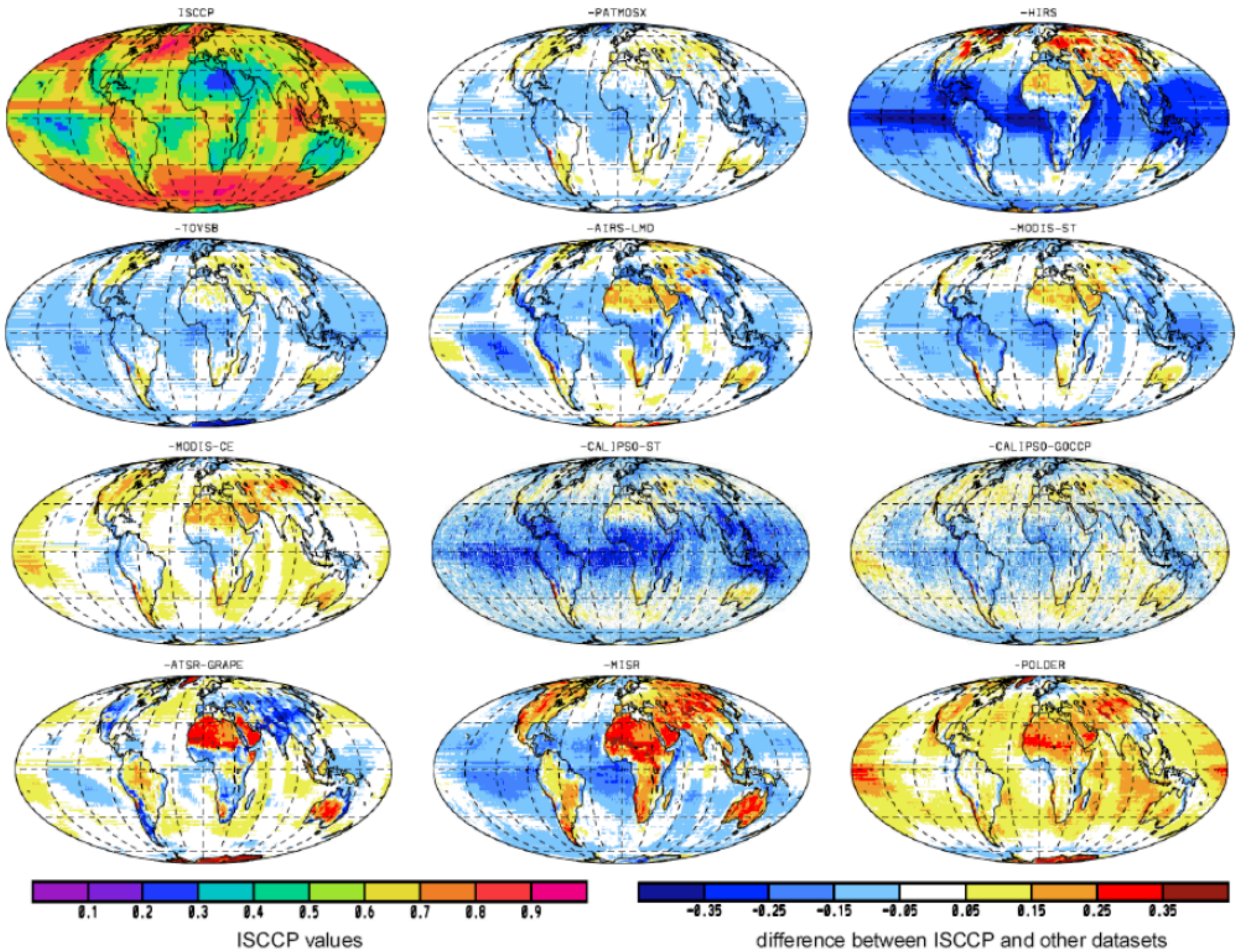
North Slope of Alaska Barrow

Uncertainty in measurements



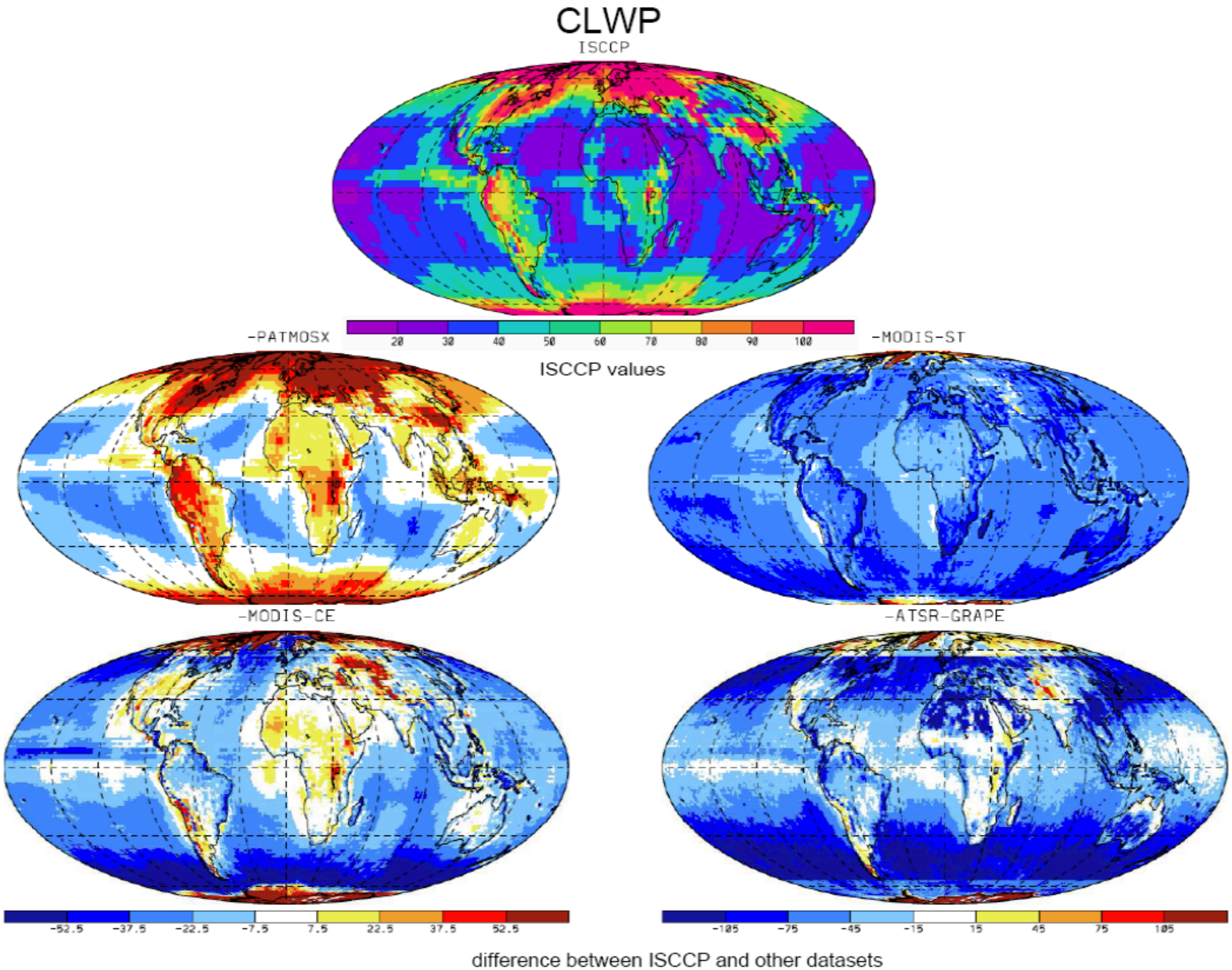
TSK = total sky cover from radiative flux measurements
TSI = cloud cover from total sky imager (picture right)
ARSCL = cloud cover from combined radar and lidar measurements

Uncertainty in measurements



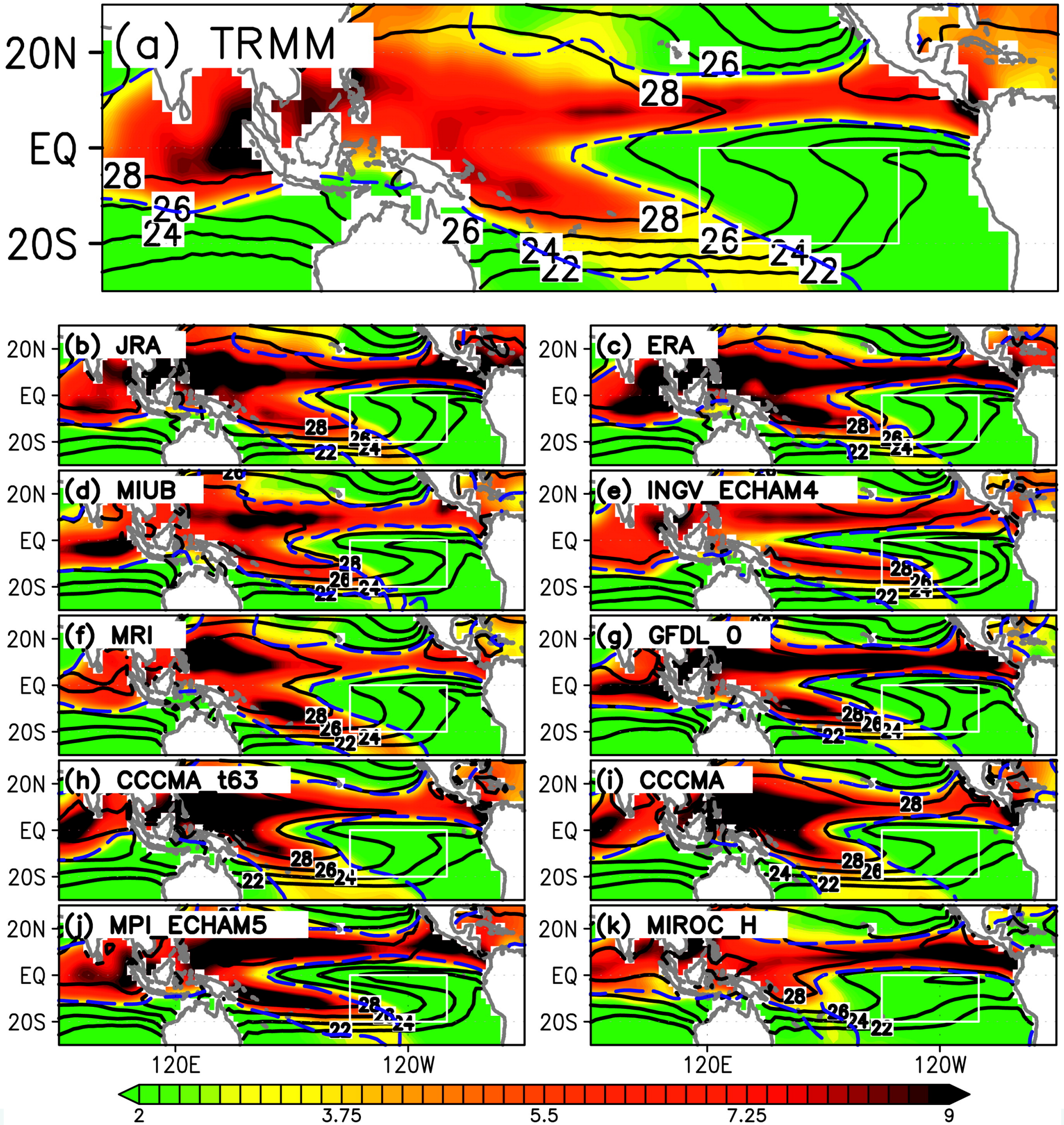
Stubenrauch, Rossow and Kinne (2012, WCRP report)

Uncertainty in measurements



Stubenrauch, Rossow and Kinne (2012, WCRP report)

Uncertainty in precipitation patterns



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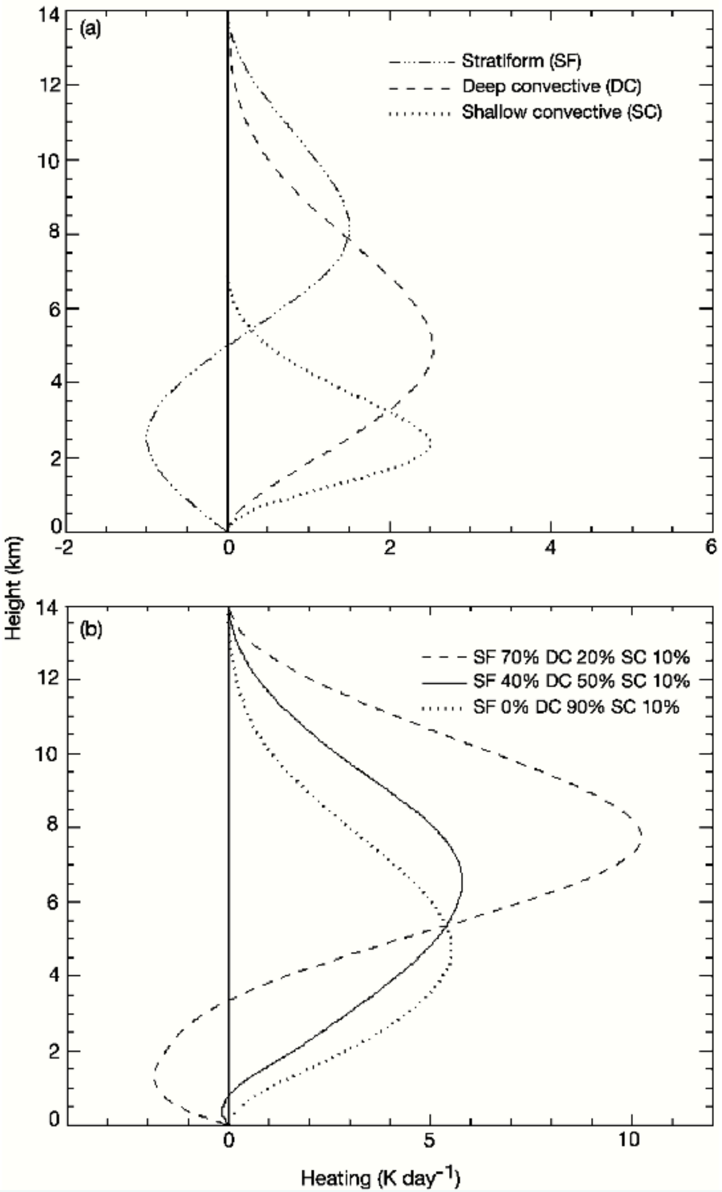
Hirota et al (2011)

Distribution of heating impacts the circulation

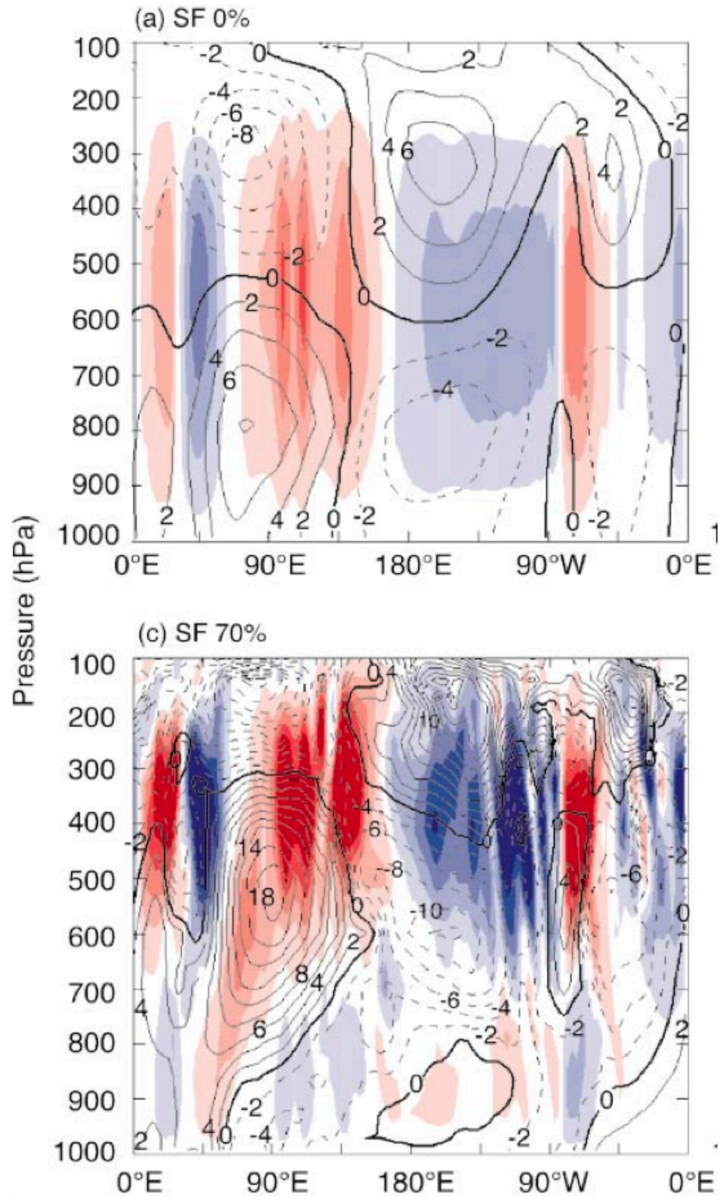


more stratiform rain leads to a stronger vertical gradient of heating at upper levels

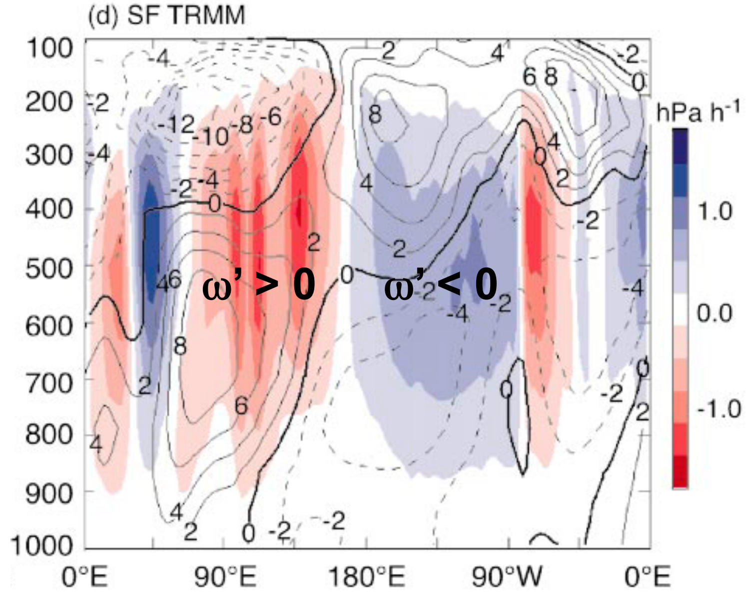
Schumacher et al (2003)

Distribution of heating impacts the circulation

modeled



observed



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für Meteorologie

Schumacher et al (2003)

Uncertainties in the representation of clouds affect:

The reflection, absorption and emission of radiation

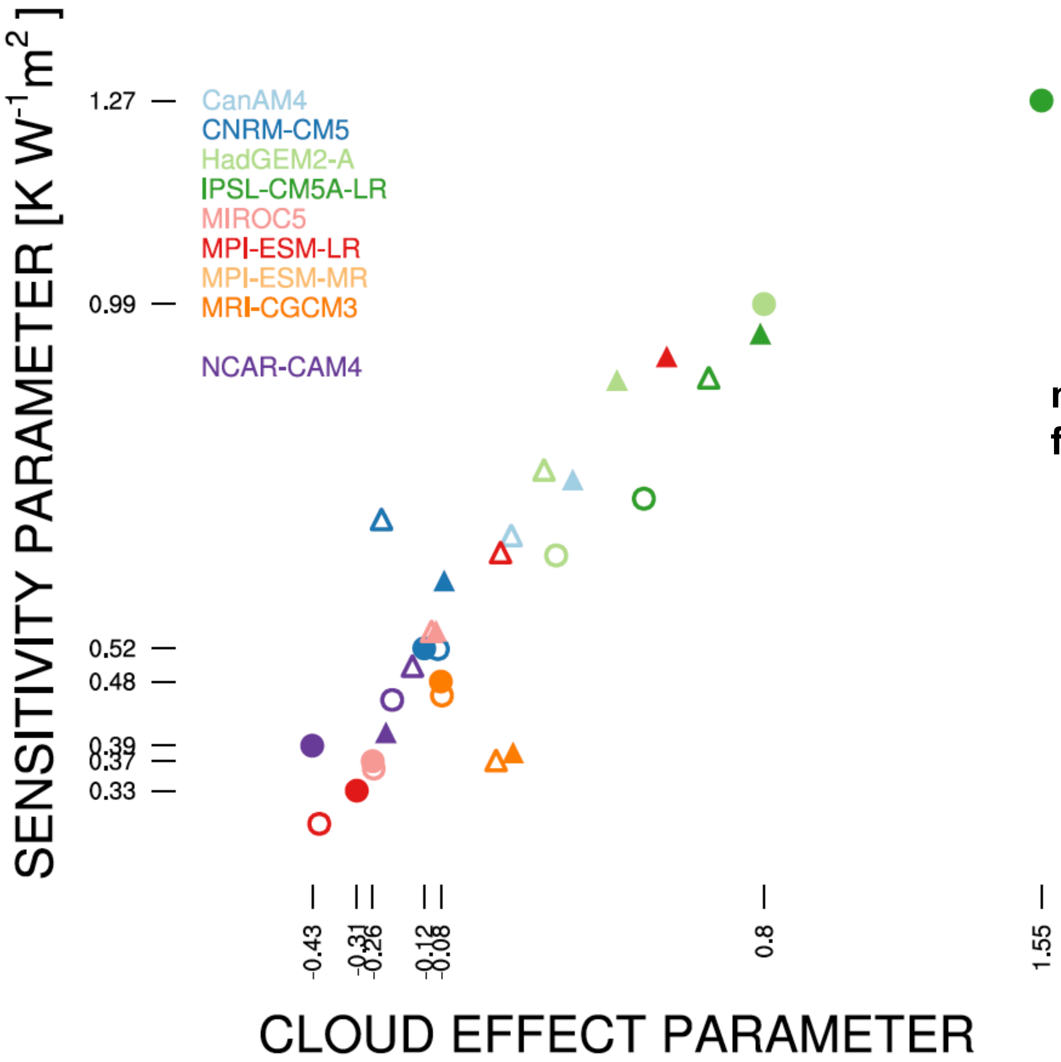
The redistribution of sensible and latent heat

The thermodynamic structure of the atmosphere

The large-scale circulation and the hydrological cycle

The coupling of the atmosphere with the ocean and with land

And thus climate sensitivity



models with a larger positive cloud feedback have a larger climate sensitivity

Figure courtesy: Brian Medeiros

Increased complexity in models

TABLE 1. Summary of parameters that have been identified as being correlated (r_{CS}) to climate sensitivity.

Parameter	r_{CS} ECHAM	IPSL	UKMO
Cloud Overshoot Parameter	+	n/a	n/a
Low Cloud Amount	+	+	+
Upper Tropospheric Vertical Resolution	−?	n/a	n/a
Entrainment (Convection)	n/a	n/a	+
Ice Fall Speed	n/a	n/a	+
Precipitation Efficiency	n/a	−	−

```
!     *Call cloud*
!
!     Input arguments.
!     ----- ----------
!   - 2D
!   paphm1   : pressure at half levels
!   papm1    : pressure at full levels
!   papp1    : pressure at full levels
!   pacdnc   : cloud droplet number concentration (speci
!   pqm1     : specific humidity
!   ptm1     : temperature
!   pxlm1    : cloud liquid water
!   pxim1    : cloud ice
!   pxtec    : detrained convective cloud liquid water or cloud ice (n)
!   pxvar    : distribution width (b-a)                             (n-1)
!   pxskew   : beta shape parameter "q"                             (n-1)
!   pbetaa   : the beta distribution minimum a                      (n-1)
!   pbetab   : the beta distribution maximum b                      (n-1)
!   pvdiffp  : the rate of change of q due to vdiff scheme          (n-1)
!   phmixtau : mixing timescale**-1 for horizontal turbulence       (n)
!   pvmixtau : mixing timescale**-1 for horizontal turbulence       (n)
!
!   - 1D
!   knvb     :
!
!     Output arguments.
!     ------ ----------
!   - 1D
!   prsfl    : surface rain flux
!   pssfl    : surface snow flux
!
!     Input, Output arguments.
!     ------------ ----------
!   - 2D
!   paclc    : cloud cover  (now diagnosed in cover)
!   paclcac  : cloud cover, accumulated
!   paclcov  : total cloud cover
!   paprl    : total stratiform precipitation (rain+snow), accumulated
!   pqvi     : vertically integrated spec. humidity, accumulated
!   pxlvi    : vertically integrated cloud liquid water, accumulated
!   pxivi    : vertically integrated cloud ice, accumulated
!   ptte     : tendency of temperature
```

```
MODULE mo_cloud_optics

  USE mo_kind,      ONLY: wp
  USE mo_constants, ONLY: api,rhoh2o
  USE mo_exception, ONLY: finish

  IMPLICIT NONE
  PRIVATE
  PUBLIC :: setup_cloud_optics, cloud_optics

  INTEGER, PARAMETER :: jpband=16

  REAL (wp), PARAMETER ::    &
       ccwmin = 1.e-7_wp,    & !< min condensate for lw cloud opacity
       reimn  = 10.0_wp,     & !< min ice effective radius (microns)
       reimx  = 150.0_wp,    & !< max ice effective radius (microns)
       relmn  = 4.0_wp,      & !< min liquid effective radius (microns)
       relmx  = 24.0_wp,     & !< max liquid effective radius (microns)
       zkap_cont = 1.143_wp, & !< continental (Martin et al. ) breadth parameter
       zkap_mrtm = 1.077_wp    !< maritime (Martin et al.) breadth parameter

  LOGICAL, SAVE    :: l_variable_inhoml = .TRUE.

  REAL (wp), SAVE :: &
       zasic,        & !< scaling constant for ice-cloud asymmetry factor
       zinpar,       & !< exponent for variable liquid-cloud inohomgeneity
       zinhomi,      & !< ice-cloud inohomogeneity factor
       cnst_zinhoml    !< constant value for liquid-cloud inhomogeneity factor
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```


Need for COOKIE's?

Key issue

The incredibly rich nature of clouds can simply not be described with a single physical law that captures all processes and their interactions, across all the scales that they encompass

but this is what models need (parameterization)

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The incredibly rich nature of clouds can simply not be described with a single physical law that captures all processes and their interactions, across all the scales that they encompass

but this is what models need (parameterization)

Parameterizations are developed based on a limited and idealized set of cases, that may not represent the conditions experienced in climate models

The parameters used are not or difficult to observe

Models have grown increasing complex

Do we understand what processes are key?

From observations alone it is hard to disentangle processes

Synthesizing modeling and observational work is challenging

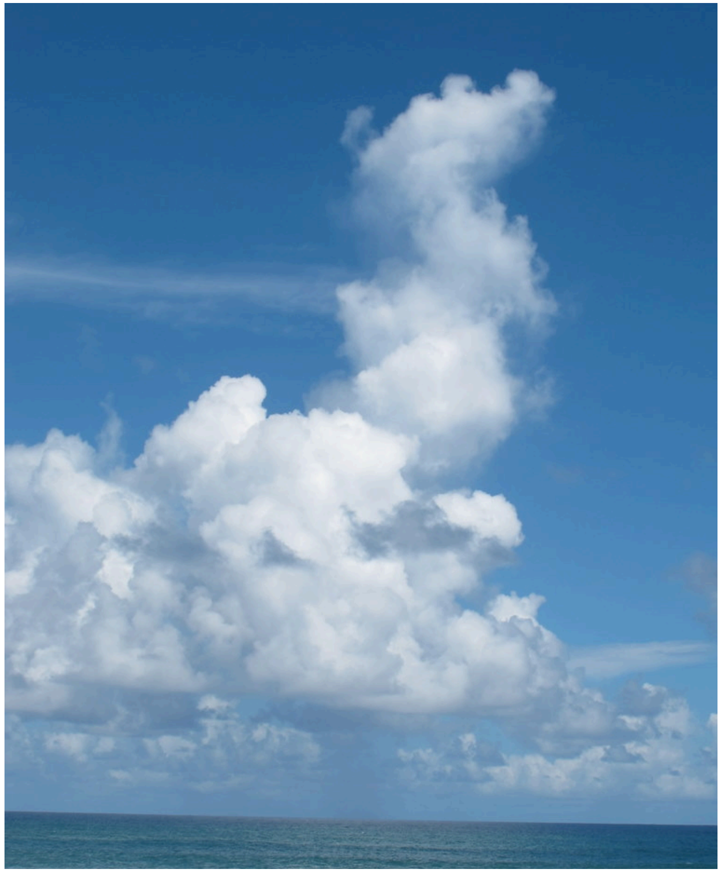
Key issue

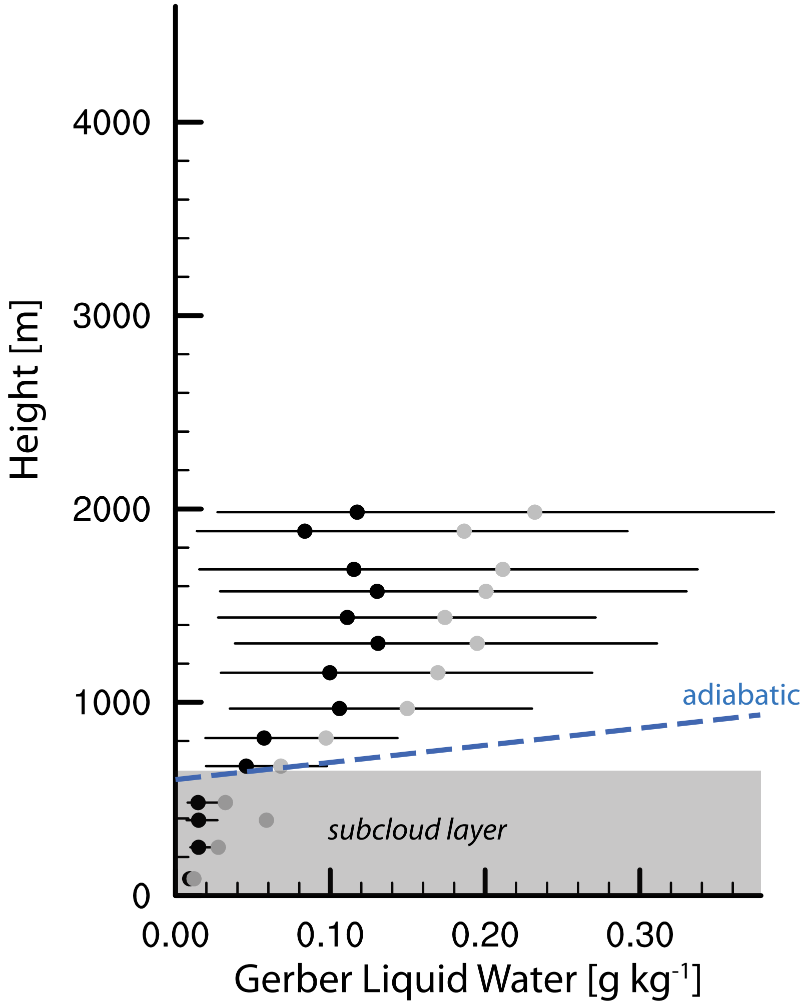
Two examples:

edges of clouds (entrainment)

cloud clumping (organization)

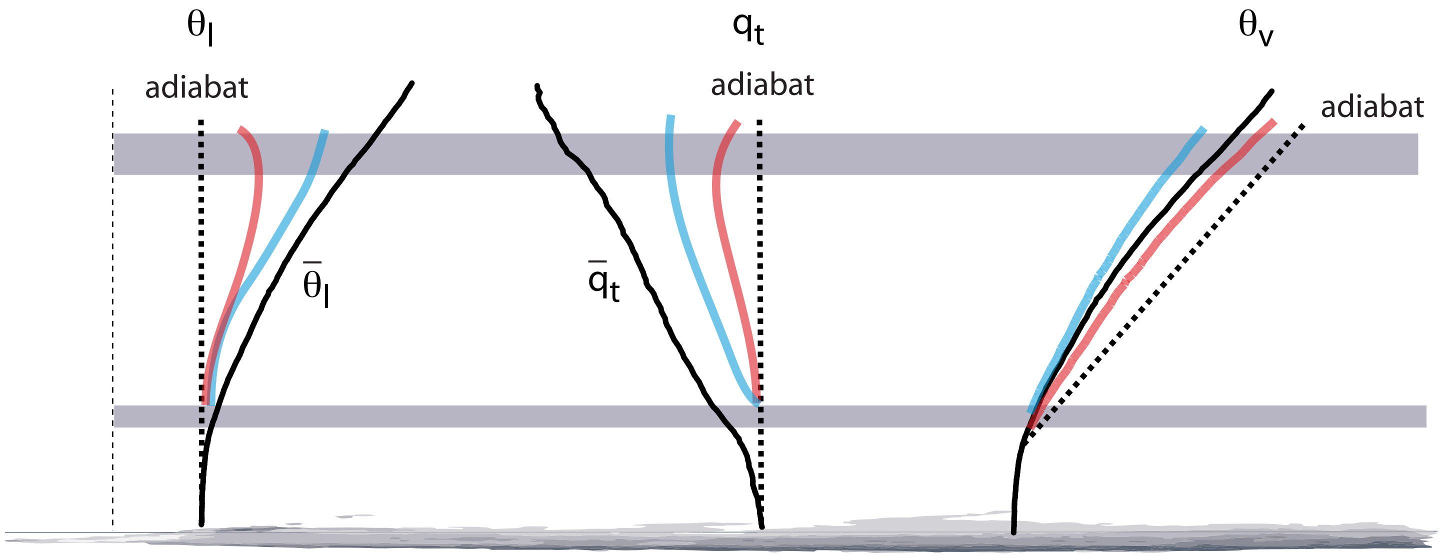
Edges of clouds (entrainment)





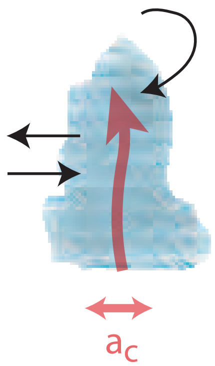
Medeiros and Stevens (2010)

The edges of clouds (entrainment)



adiabat / no mixing

mean profile (~ environment)



cloud core samples ($q_l > 0, \theta_v' > 0$)

cloud samples ($q_l > 0$)

cloud parcels become negatively buoyant when cooling due to evaporation of cloud droplets due to entrainment drying exceeds entrainment warming

Observations dispute applicability bubble theories to cumulus

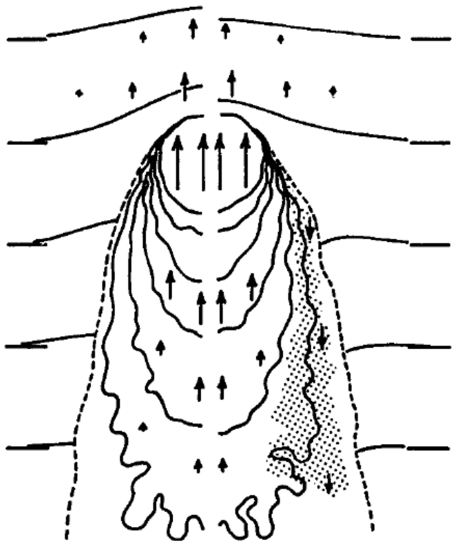
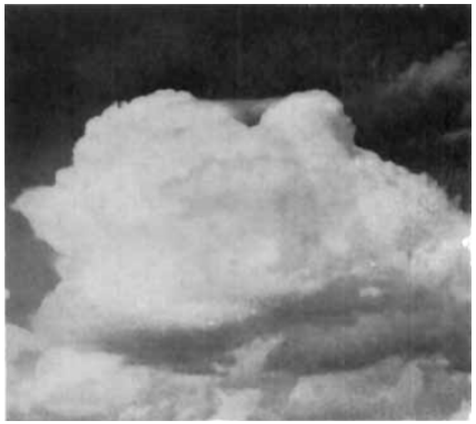
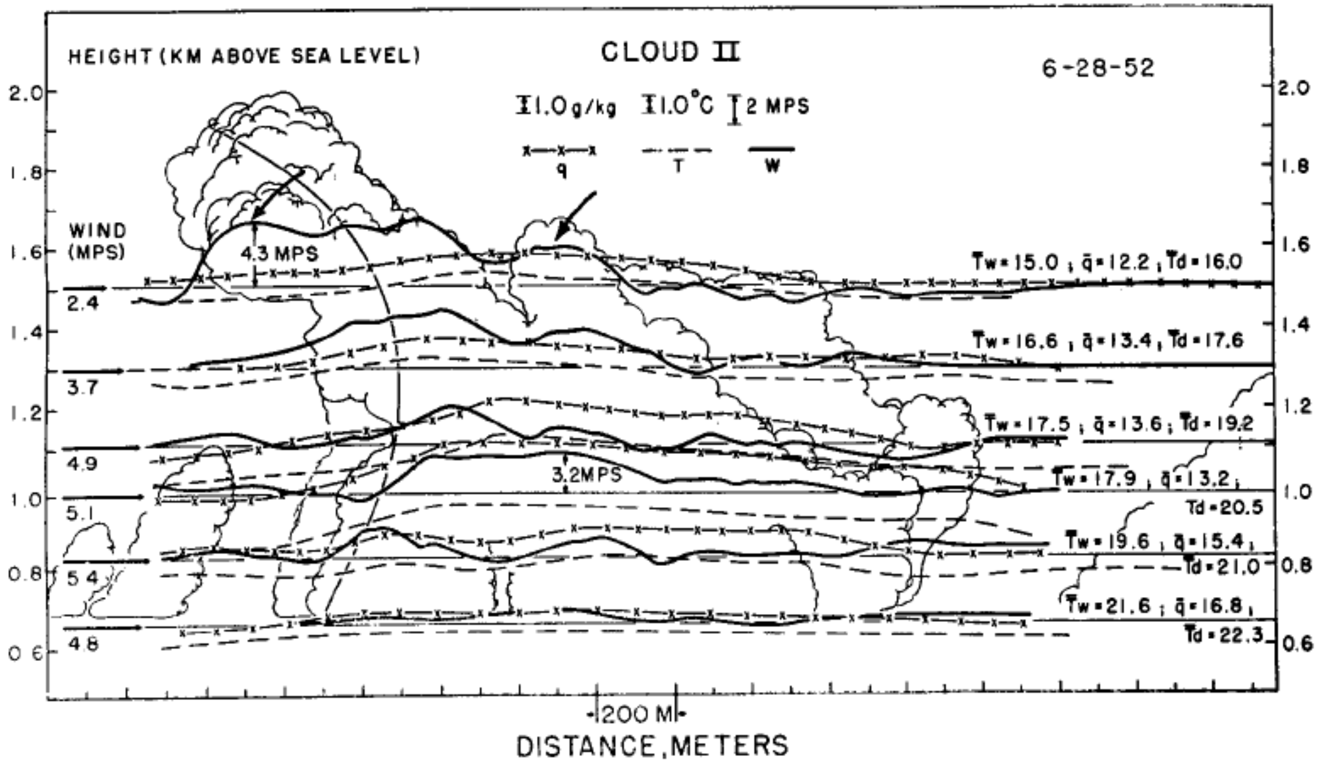


Figure 3. The velocity field around a rising bubble.





Heavy correspondence making some important points

Malkus: "The next steps in cumulus studies should be, in contrast to synthesizing parameters and introduction of empirical constants, an attempt to eliminate these by determining a functional form for entrainment rate involving as many variables as may be necessary to construct a timedependent, life-cycle model.

…

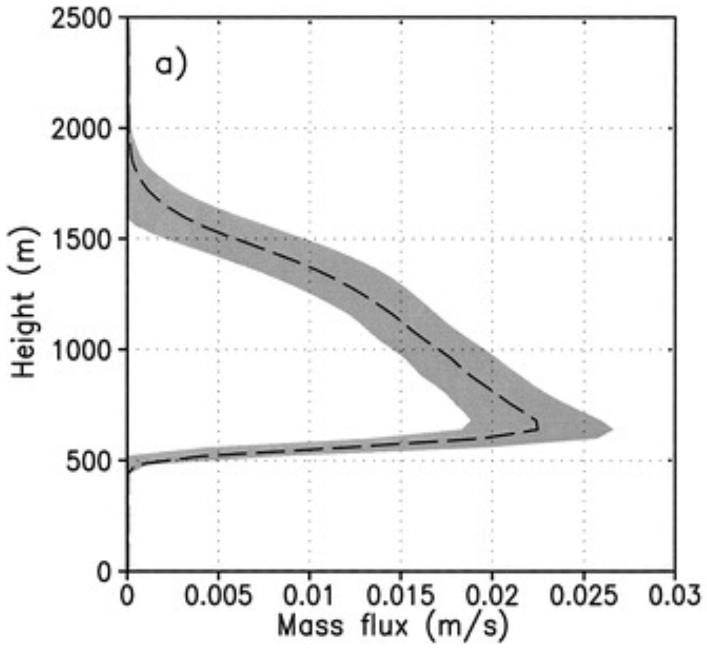
In conclusion, this writer is gratified to perceive that, despite their continuing scepticism toward contributions reaching them from this side of the Atlantic. Scorer and Ludlam have finally discovered for themselves that mixing between cumulus clouds and the surrounding air is of some non-negligible significance."

Scorer and Ludlam: "The real issue is not whether Dr. Malkus's half-dozen disposable constants or our disposable form is to be fitted to the observations, but whether the one theory or the other helps us to understand what is actually happening during convection."

How to quantify a process such as entrainment?

Malkus (1953,1964), Scorer and Ludlam (1953)

It is deducible, not (yet) predictable, but crucial



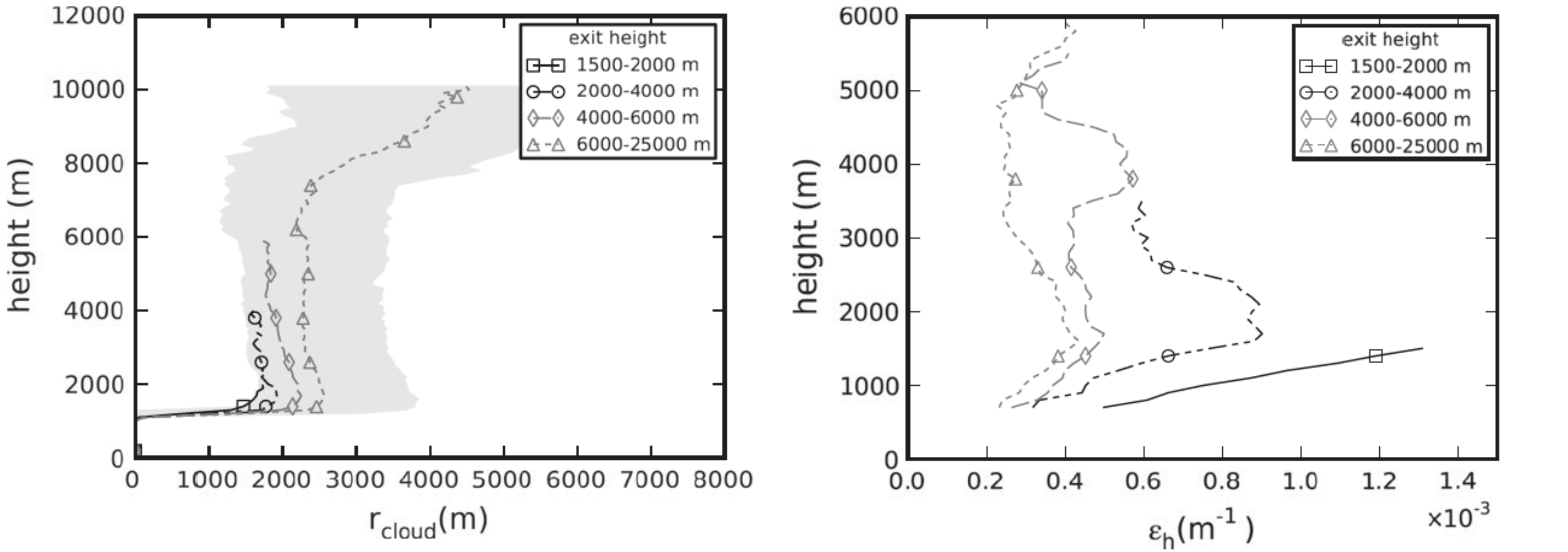
$$\frac{1}{M}\frac{\partial M}{\partial z} \approx \varepsilon$$

```
MODULE mo_cumulus_flux

  USE mo_kind, ONLY: dp

  IMPLICIT NONE

  ! -----------------------------------------------------------------
  !
  ! module *mo_cumulus_flux* - parameters for cumulus massflux scheme
  !
  ! -----------------------------------------------------------------

  REAL(dp) :: entrpen      !    entrainment rate for penetrative convection
  REAL(dp) :: entrscv      !    entrainment rate for shallow convection
  REAL(dp) :: entrmid      !    entrainment rate for midlevel convection
  REAL(dp) :: entrdd       !    entrainment rate for cumulus downdrafts
  REAL(dp) :: centrmax     !
  REAL(dp) :: cmfctop      !    relat. cloud massflux at level above nonbuoyanc
  REAL(dp) :: cminbuoy     !    minimum excess buoyancy
  REAL(dp) :: cmaxbuoy     !    maximum excess buoyancy
  REAL(dp) :: cbfac        !    factor for std dev of virtual pot temp
  REAL(dp) :: cmfcmax      !    maximum massflux value allowed for
  REAL(dp) :: cmfcmin      !    minimum massflux value (for safety)
  REAL(dp) :: cmfdeps      !    fractional massflux for downdrafts at lfs
  REAL(dp) :: rhcdd        !    relative saturation in downdrafts
  REAL(dp) :: cprcon       !    coefficients for determining conversion
                       !    from cloud water to rain
  INTEGER :: nmctop    !    max. level for cloud base of mid level conv.


CONTAINS

SUBROUTINE cuparam

...
  !  Executable Statements

!-- 1. Specify parameters for massflux-scheme

  entrpen = 1.0E-4_dp !
  entrscv = 3.0E-4_dp
  cminbuoy = 0.1_dp
  cmaxbuoy = 1.0_dp
  cbfac    = 1.0_dp
  entrmid = 1.0E-4_dp ! Average entrainment rate for midlevel convection
  entrdd = 2.0E-4_dp ! Average entrainment rate for downdrafts
  centrmax= 3.E-4_dp !
  cmfcmax = 1.0_dp ! Maximum massflux value allowed for updrafts etc
  cmfcmin = 1.E-10_dp ! Minimum massflux value (for safety)
  cmfdeps = 0.3_dp ! Fractional massflux for downdrafts at lfs
```


Siebesma et al (2006)

How do clouds get deep?

Malkus: "We learned that cumulus clouds, like people, go through a life cycle; they are born, grow to maturity, age and die. Unlike people, however, the fatter they are the longer they live, and the taller and more successful they grow"



Boing et al. (2012)

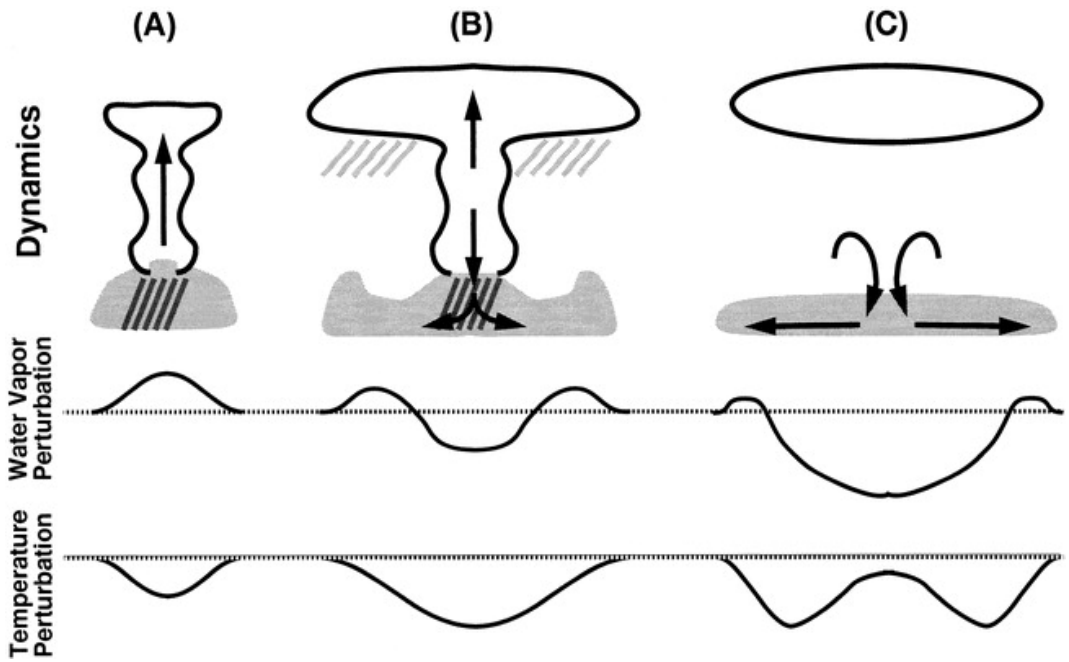
Clustering of clouds (organization)

Forcing by hotspots

Latent heat release induced mesoscale circulations

Downdrafts trigger formation of clouds nearby

Mutual protection hypothesis



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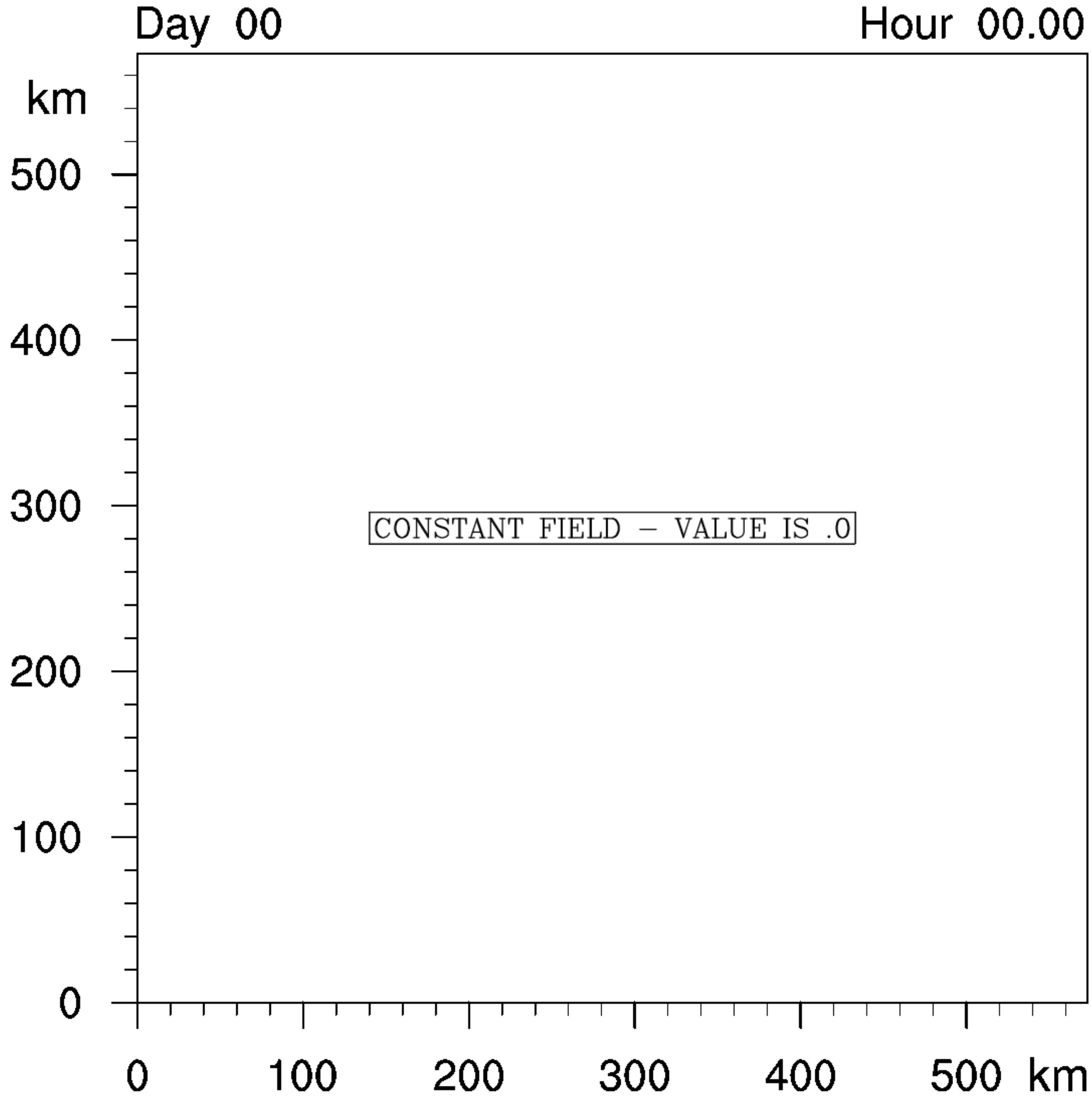
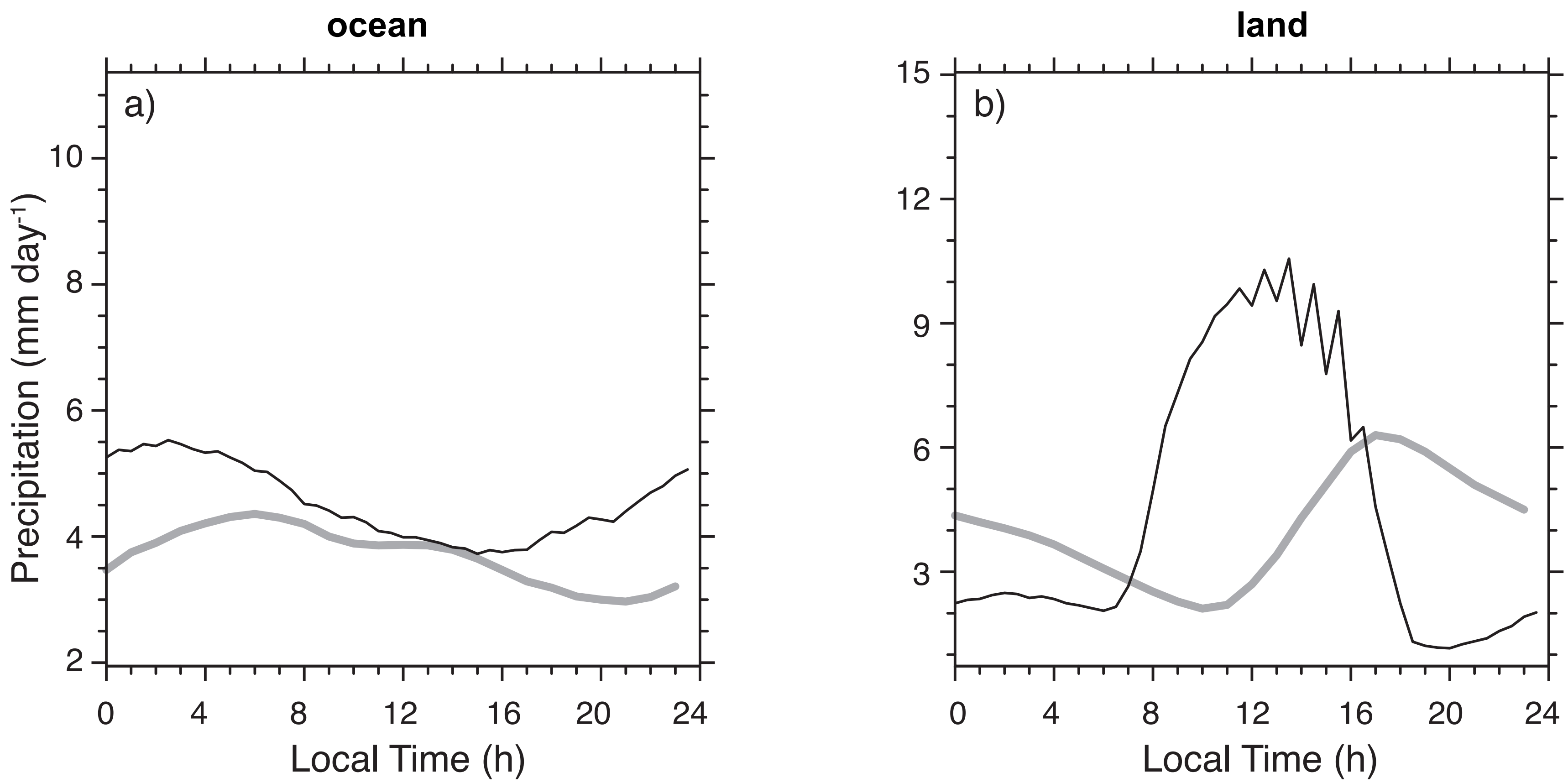
Malkus (1957), Zipser (1969), Lopez (1978), Randal and Huffman(1980),Tompkins (2001)


Day 00
Hour 00.00
km
500
400
300
200
100
0
CONSTANT FIELD – VALUE IS .0
0
100
200
300
400
500 km

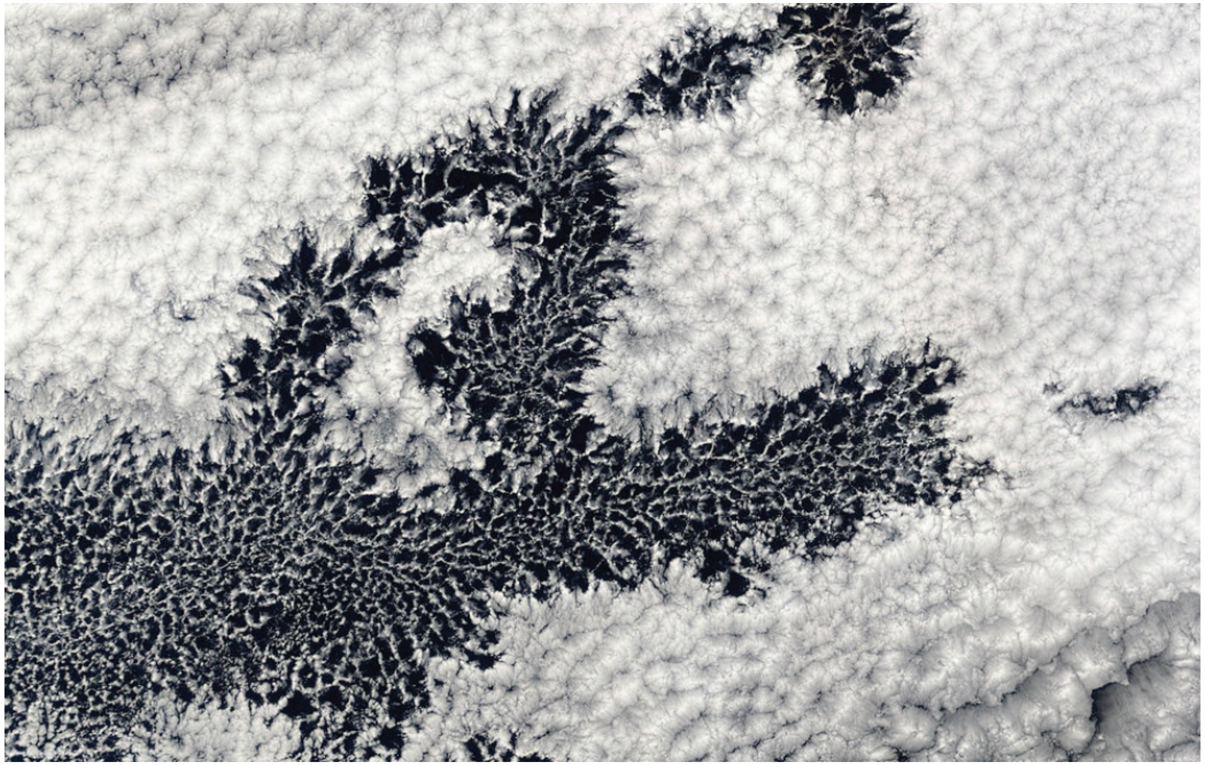
Entrainment and organization affect precipitation globally

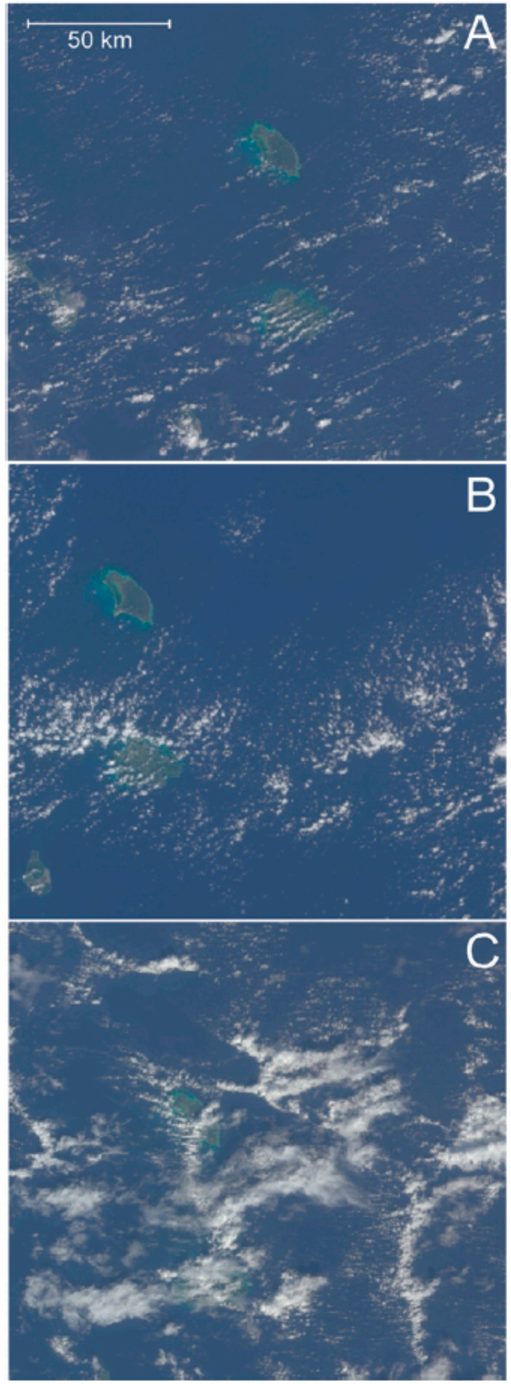


Entrainment affects the magnitude of precipitation maximum, organization affects the timing of the precipitation maximum

Hohenegger and Stevens (2013)

Not just in deep convection





How does shallow convection organize?

How does the albedo change?

Figure from B. Stevens, Snodgrass et al (2009), Zuidema et al (2012), Terai and Wood (2013)

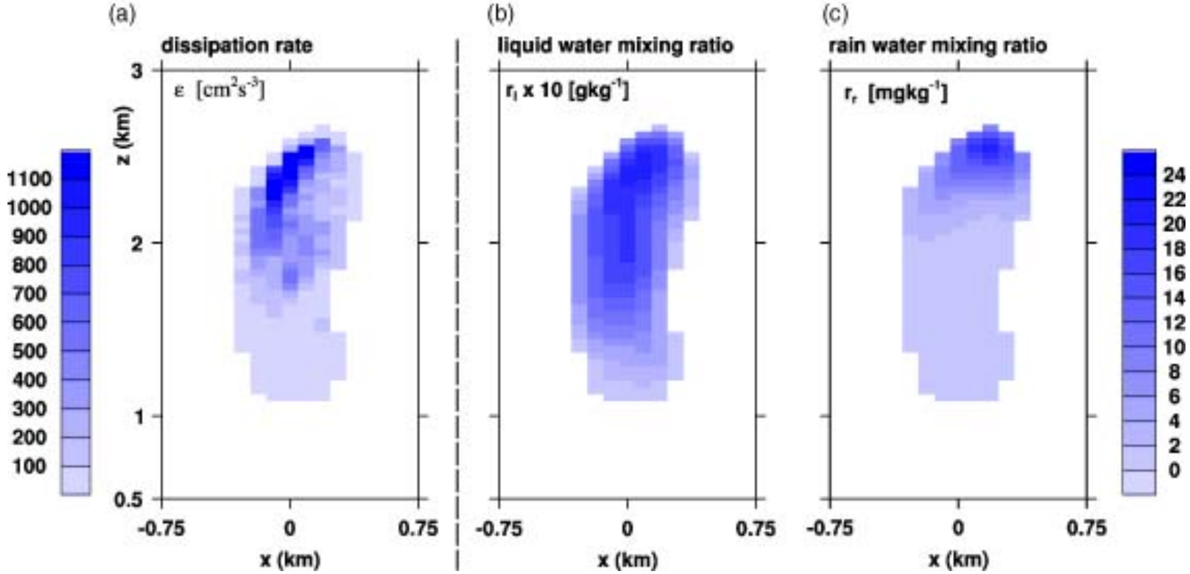
If precipitation is key …

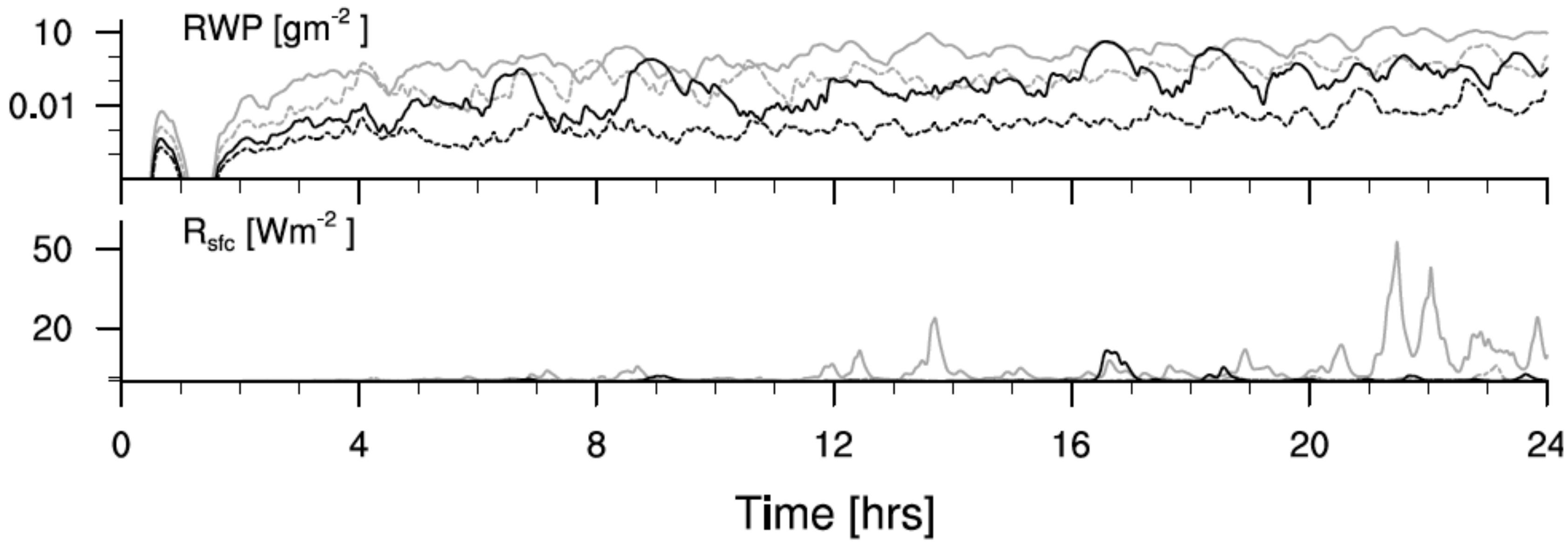
turbulence-enhanced coalescence applied?

yes / no

N = 300 cm^{-3} —— (yes) ‐ ‐ ‐ ‐ (no)

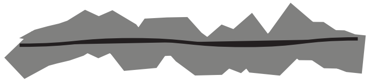
N = 140 cm^{-3} —— (yes) ‐ ‐ ‐ ‐ (no)





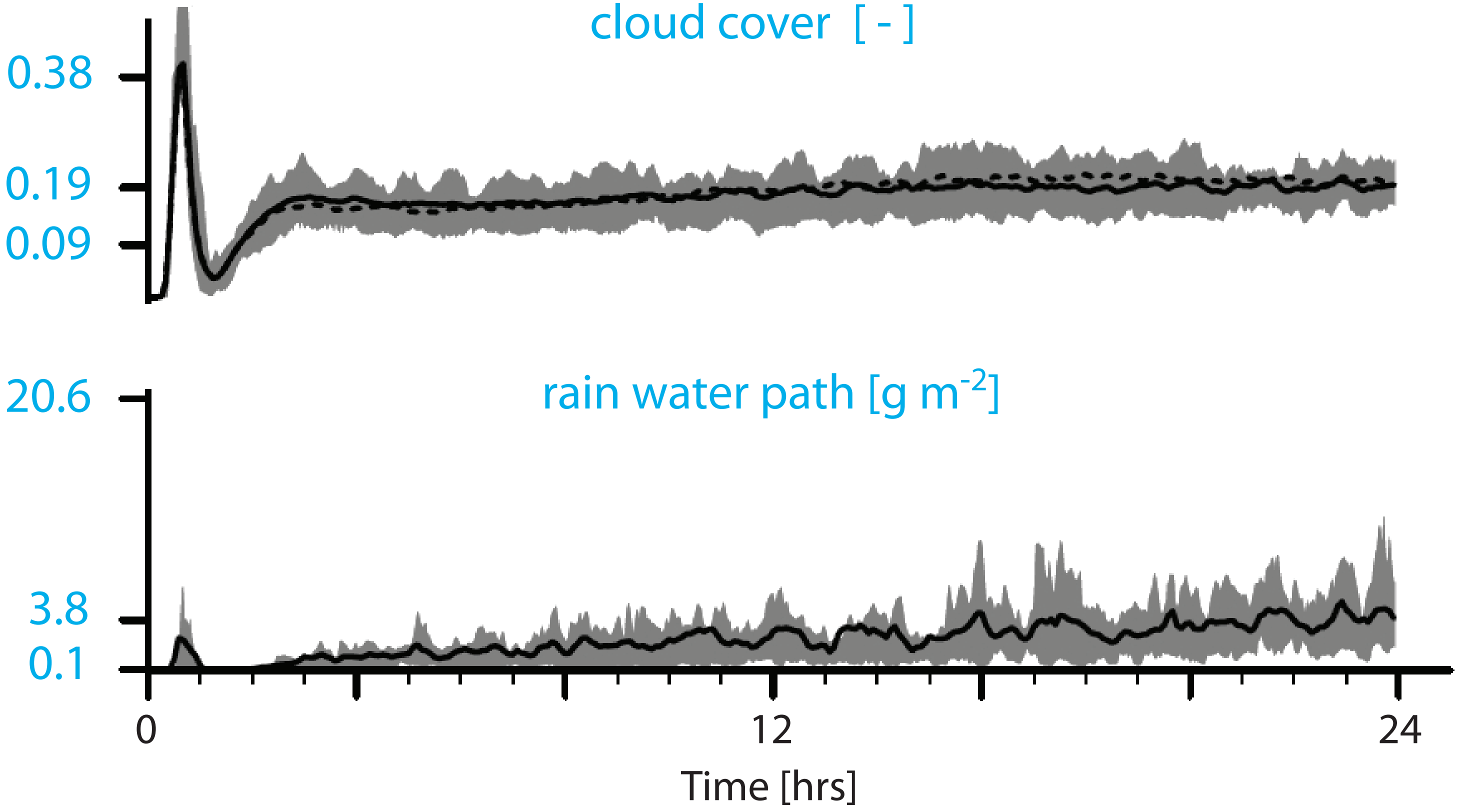
Seifert et al. (2010)

Uncertainties in Large Eddy Simulation



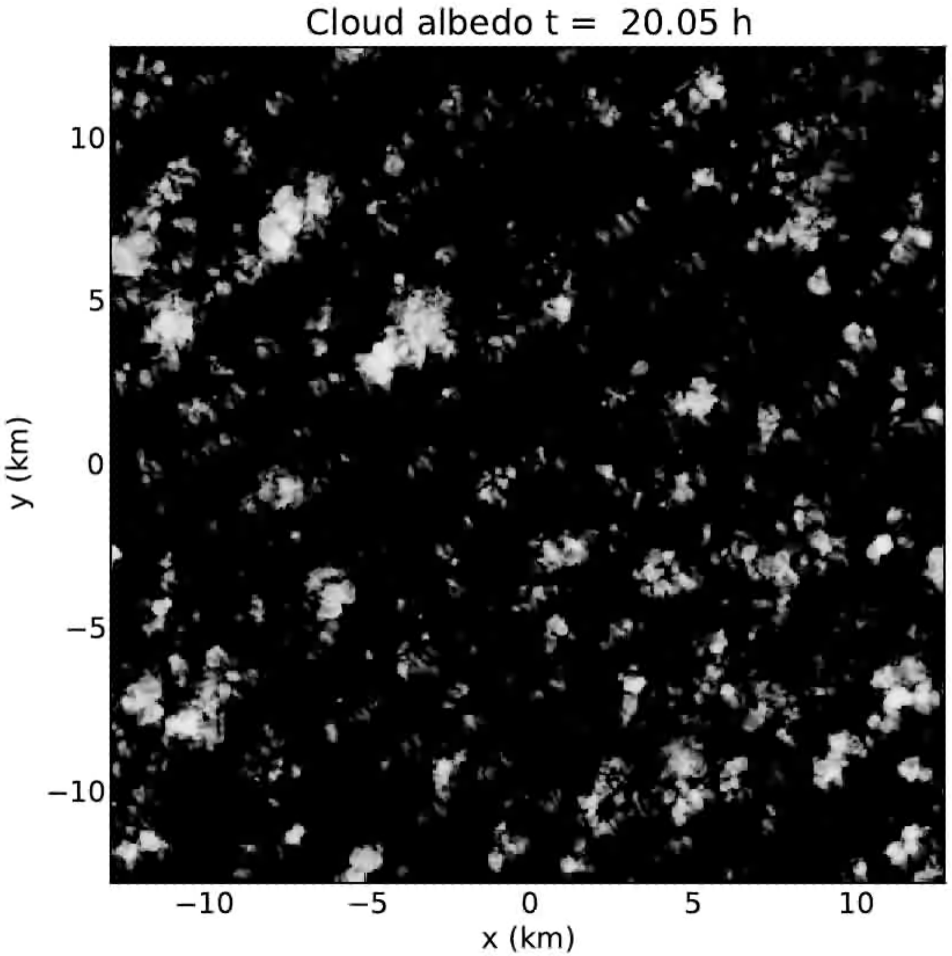
Shading represents inter-quartile spread of an ensemble of 14 LES codes

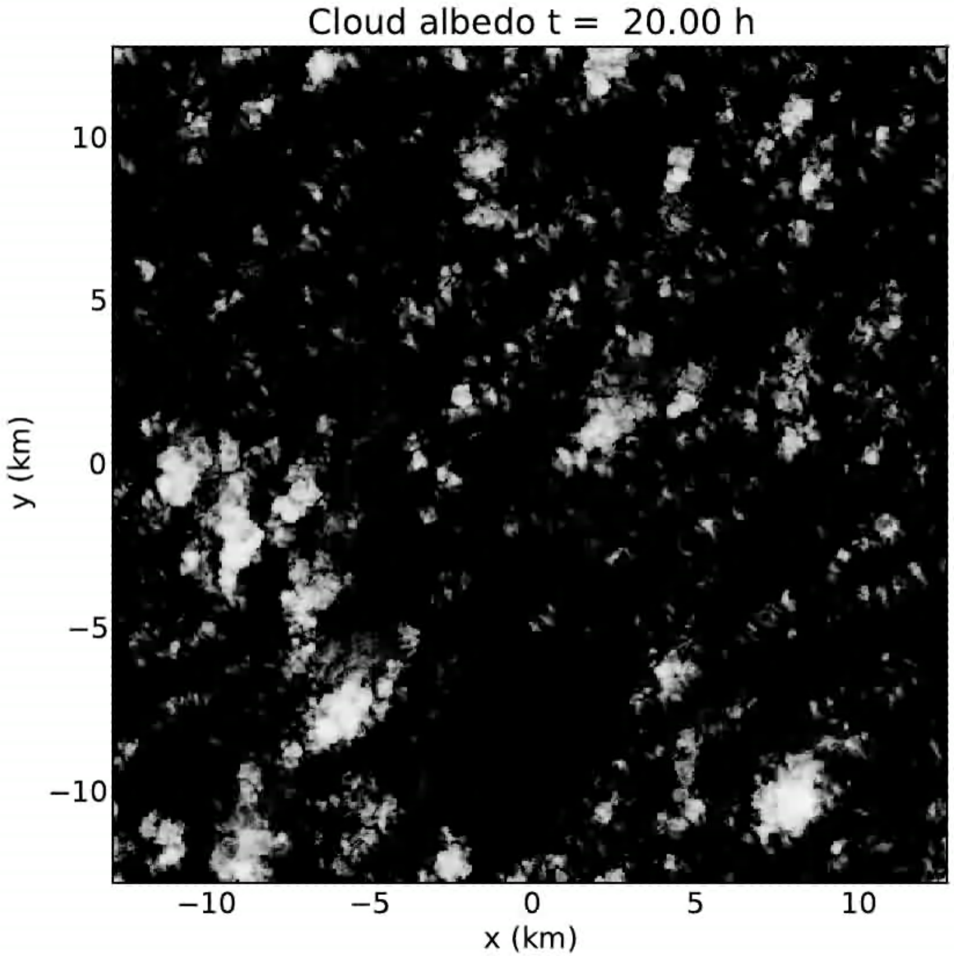
Values on y-axis represent the maximum, minimum and mean of the full ensemble



Van Zanten et al. (2012, JAMES)

Organization in large domain high resolution LES runs





Challenges

Small scale processes may have large scale effects, but are hard to observe and model on large scales

Small scale experiments lack realistic large scale motions

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What is the relative role of different processes in controlling cloud distributions?

Large-scale motions versus small-scale motions?

Meteorology versus chemistry (aerosol)?

How do we use high resolution models and observations to guide climate modeling?

On the bright side

We will get more Vitamin D

There are job opportunities for you!

Recap

Clouds can be viewed in different ways

Our understanding of clouds is the result of decades of research that were driven by various scientific interests

There is considerable insight into the behavior of clouds

These studies have led to the development of many simulations, conceptual models and sophisticated measurements

The increase in capability and information however has also led to more complexity and possibilities

The rich nature of clouds may affect climate in different ways

You may help decipher which ones matter

The next two weeks

Part 1:

Clouds as radiative, (thermo)-dynamic and microphysical entities

Part 2:

Modeling and observation of clouds across scales

Part 3:

The interaction of clouds with other processes in the climate system