Deutscher Wetterdienst
Wetter und Klima aus einer Hand




Clouds in Data Assimilation (DA)

Olaf Stiller, DWD

- Clouds in the atmosphere and NWP models

- Assimilation in cloudy air
  - Ensemble Kalman Filter vs. Variational DA
  - Cloud screening
  - Assimilation of cloudy radiances

This is not covered in this talk:

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- Cloud radars/lidars
  - ground based
    - cloud radar/lidar networks (research facilities)
    - ceilometers (nadir pointing, height of lower cloud edge)
  - space based (research satellites/missions)
    - A Train (Cloudsat/Calipso)
    - Earthcare mission (start 2013 ???)

- Assimilation of precipitation
  - latent heat nudging
  - in 4D Var (directly)

- Retrieval vs Radiances (raw-data)

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What is covered?

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- Clouds
  - stability and clouds (why are clouds in the atmosphere?)
  - where do clouds occur?
  - clouds in NWP models
    - parametrisations
    - interactions and impact
- Assimilation in cloudy air
  - Ensemble Kalman Filter vs. Variational DA
  - Cloud screening
  - Assimilation of cloudy radiances
    - Infrared vs microwave
    - What have others done
    - A simplified model problem

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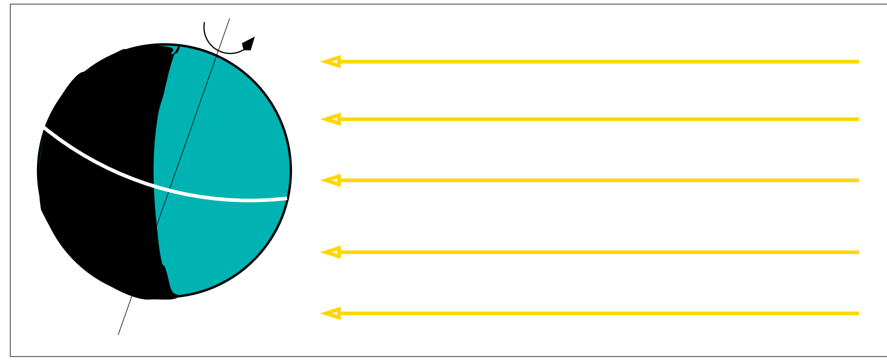
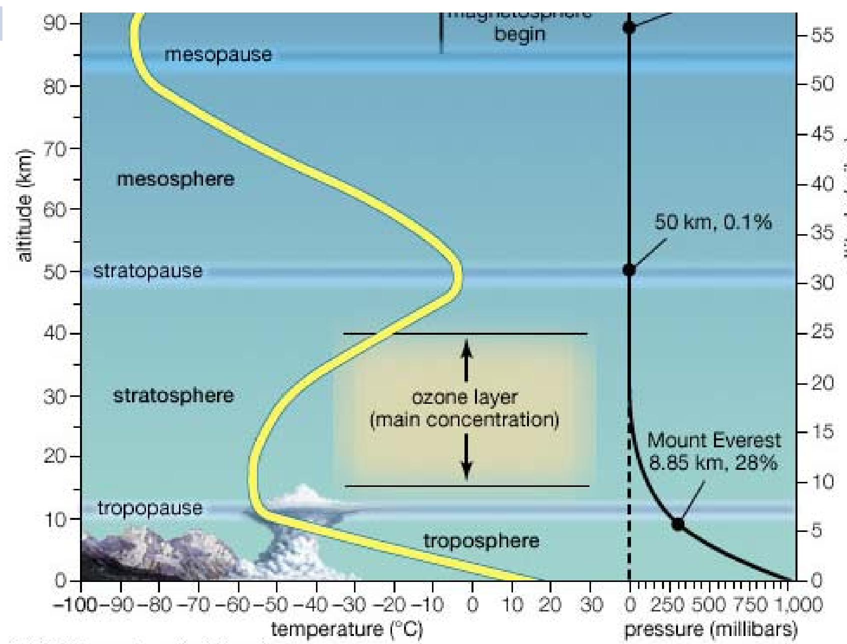
Stability and Clouds

- The earth is in radiative equilibrium but
  - heating is strongest
    - at the ground
    - in the Tropics and the Summer hemisphere
  - air in the troposphere is constantly cooled (both day and night)



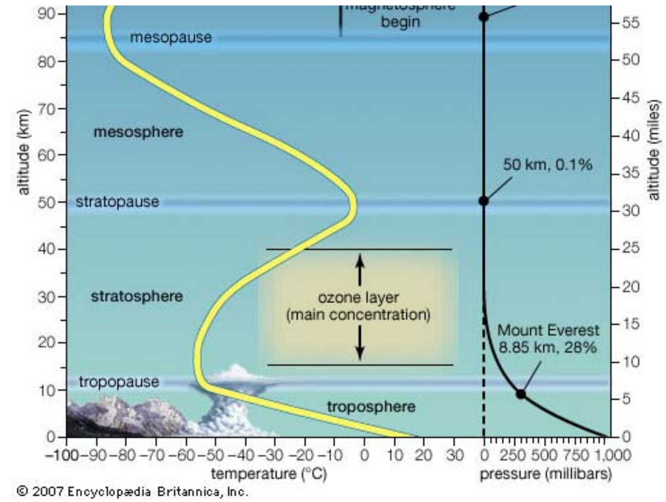
- ➢ This leads to instability
- ➢ Instability leads to convection
- ➢ Convection restores stability
- ➢ → almost neutral Temperature profile

❖ How can the troposphere get colder with height? Is this not unstable?



Stability and Clouds

- How can the troposphere get colder with height? Is this not unstable?



Air that rises becomes colder

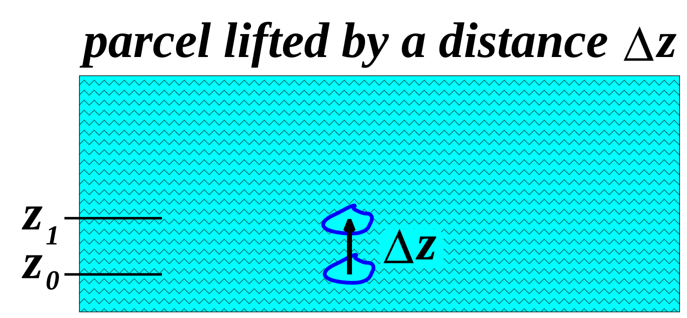
- pressure reduces -> adiabatic expansion

$$T = \left(\frac{p}{p_0}\right)^{\kappa} T_0$$

- Potential Temperature is conserved

$$\theta \equiv \left(\frac{p}{p_0}\right)^{-\kappa} T = const.$$

dry adiabat
(neutral stability profile in dry air)



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Moisture variables

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q, q : $\frac{\text{mass of H2O vapour}}{\text{total mass of air}}$ specific humidity

q_v, qv : $\frac{\text{mass of H2O vapour}}{\text{mass of dry air}}$ water vapour mixing ratio

q_l, ql : $\frac{\text{mass of liquid H2O}}{\text{mass of dry air}}$ liquid cloud water mixing ratio

q_i, qi : $\frac{\text{mass of frozen H2O}}{\text{mass of dry air}}$ frozen cloud water mixing ratio

q_c, qc $= q_l + q_i$ total cloud water mixing ratio

$q_T = q_v + q_l + q_i$ total water mixing ratio

q_r, q_s : mixing ratio of rain/snow

q_{sat} :	(T,p)	saturation value of qv w.r.t. liquid
$q_{sat,i}$:	(T,p)	saturation value of qv w.r.t. ice

$RH = \frac{q_v}{q_{sat}}$	relative humidity
$RH_T = \frac{q_T}{q_{sat}}$	total relative humidity

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Stability and Clouds

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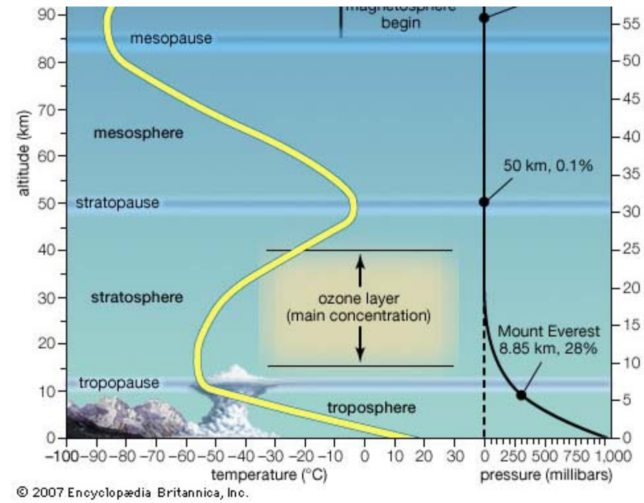
- Air that rises becomes colder
  (adiabatic expansion)

  - ➢ dry adiabat

$$\theta \equiv \left(\frac{p}{p_0}\right)^{-\kappa} T = const.$$



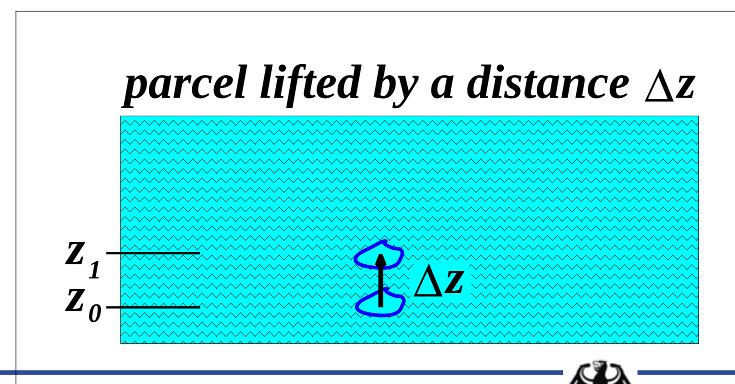
- The impact of moisture:

  In cloudy air: q_sat decreases with height

  - condensation -> latent heat release
    - ➢ potential Temperature increases with height

  - ➢ moist adiabat

$$\frac{d}{dz}\theta = \Gamma > 0$$



Stability and Clouds

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- Air that rises becomes colder (adiabatic expansion)
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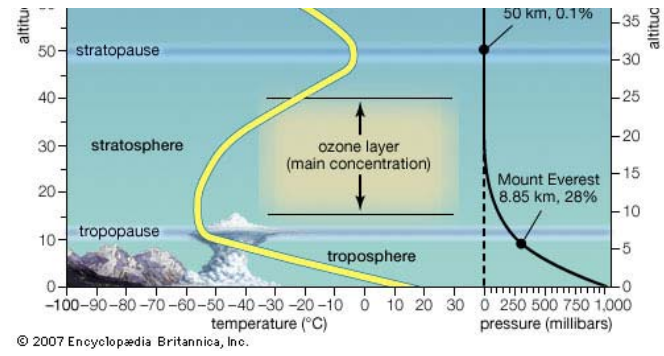

- The impact of moisture:

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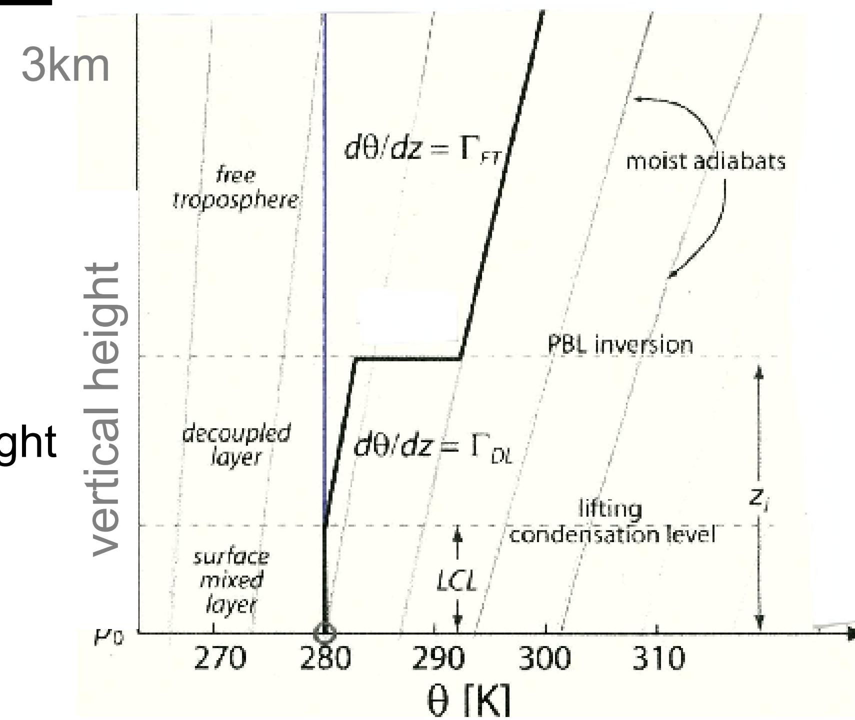

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Vertical distribution of convection

- Convection typically stops near inversions or stable layers such as:
  - tropopause (deep convection)
  - Low level inversion (shallow convection)
  - boundary layer (BL) top (dry convection or cloud topped BLs)
  - freezing level (intermediate)

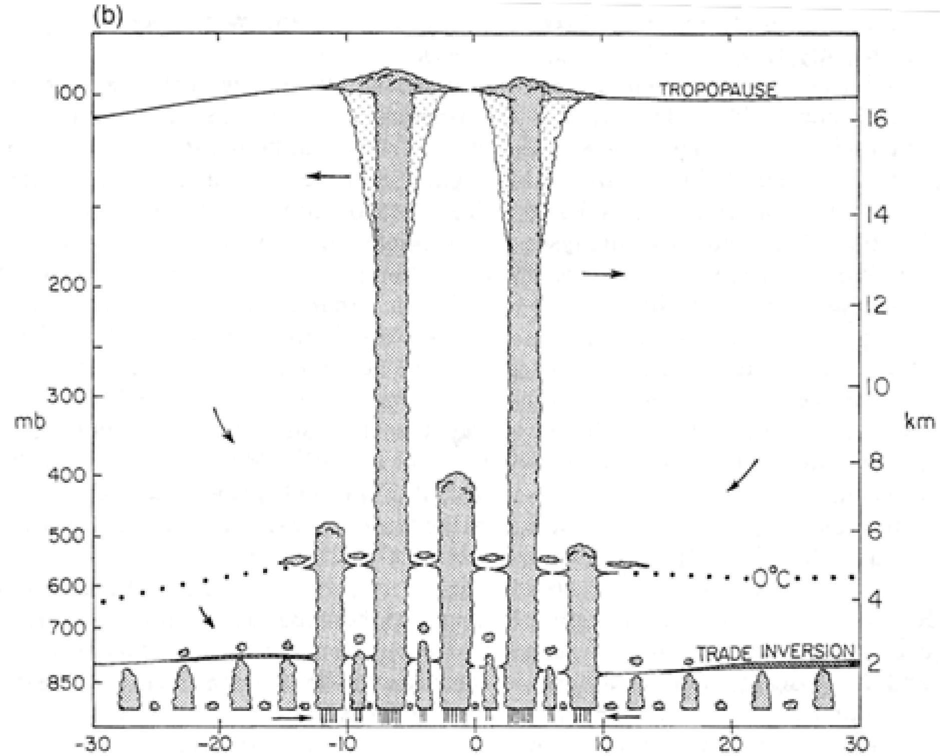

FIG. 13. (*Continued*) cloud types are indicated: shallow cumulus, cumulus congestus, and cumulonimbus. Within the shallow cumulus classification, there are two subdivisions: forced and active cumulus. Three stable layers are indicated: the trade inversion, the 0°C layer, and the tropopause. Shelf clouds and cloud debris near the trade and 0°C stable layers represent detrainment there. Cirrus anvils occur near the tropopause. Considerable overshooting of the trade and 0°C stable layers occurs in the equatorial trough zone. Arrows indicate meridional circulation. Although double ITCZ is indicated, representing IOP-mean, this structure is transient over the warm pool and a single ITCZ often exists.

Johnson et al., 1999, JCL

Horizontal distribution of clouds

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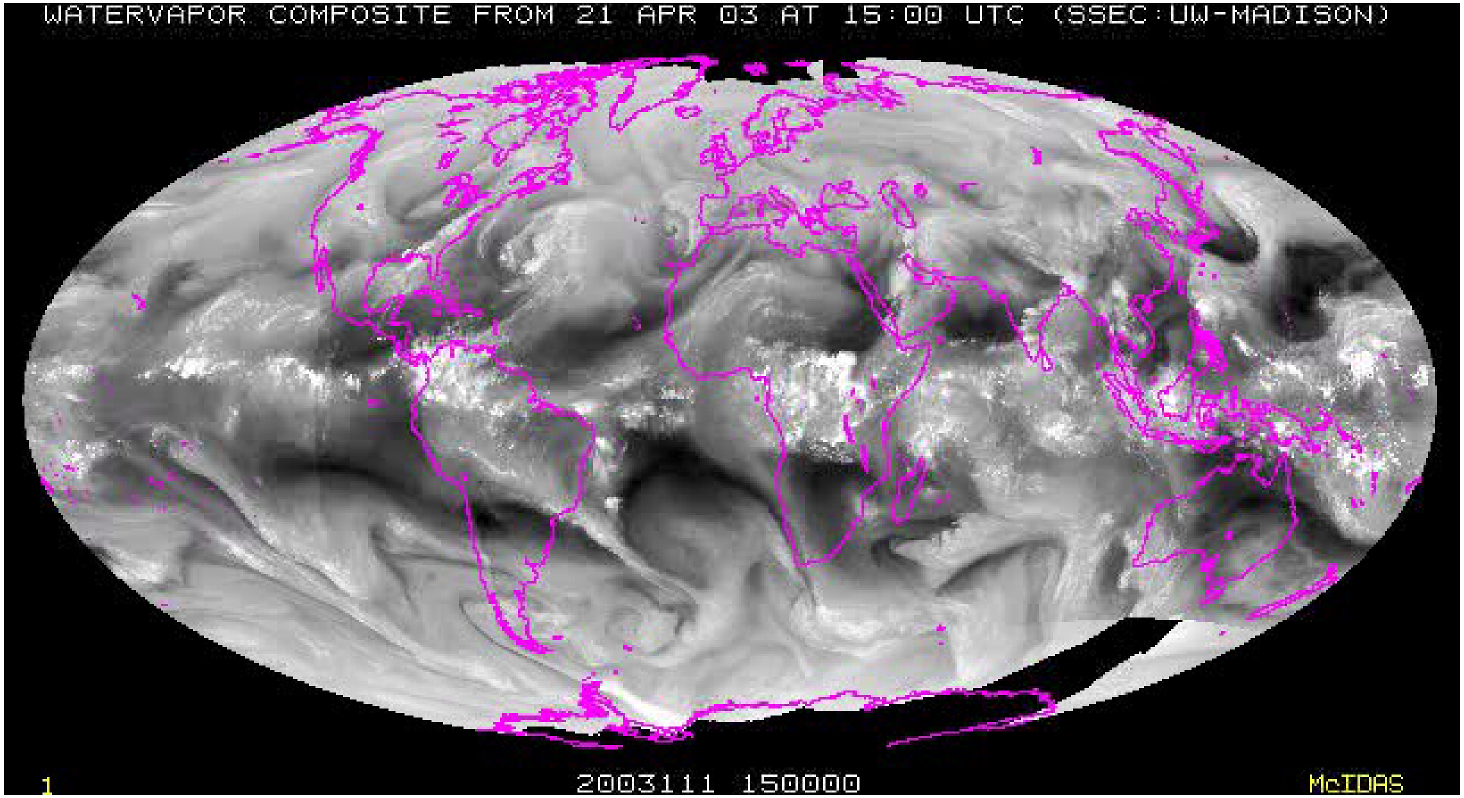
- The occurence of convection and clouds is linked to both:
  - the temperature field (horizontally smoothed through buoyancy – gravity waves)
  - the moisture field (strong horizontal variations/gradients)



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Clouds are an important part of the general circulation

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- Convection occurs where the atmosphere is most unstable
  - e.g. over warm waters, hot land (Inter-Tropical Convergence Zone – ITCZ)

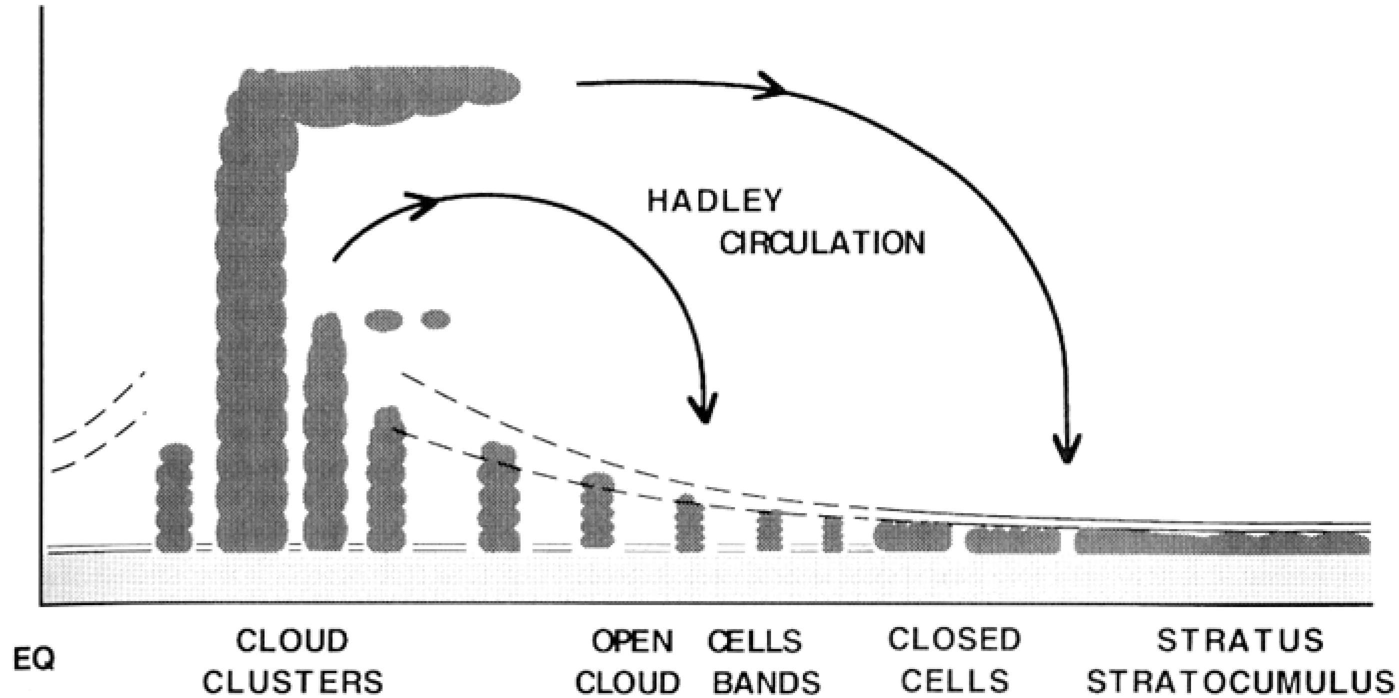
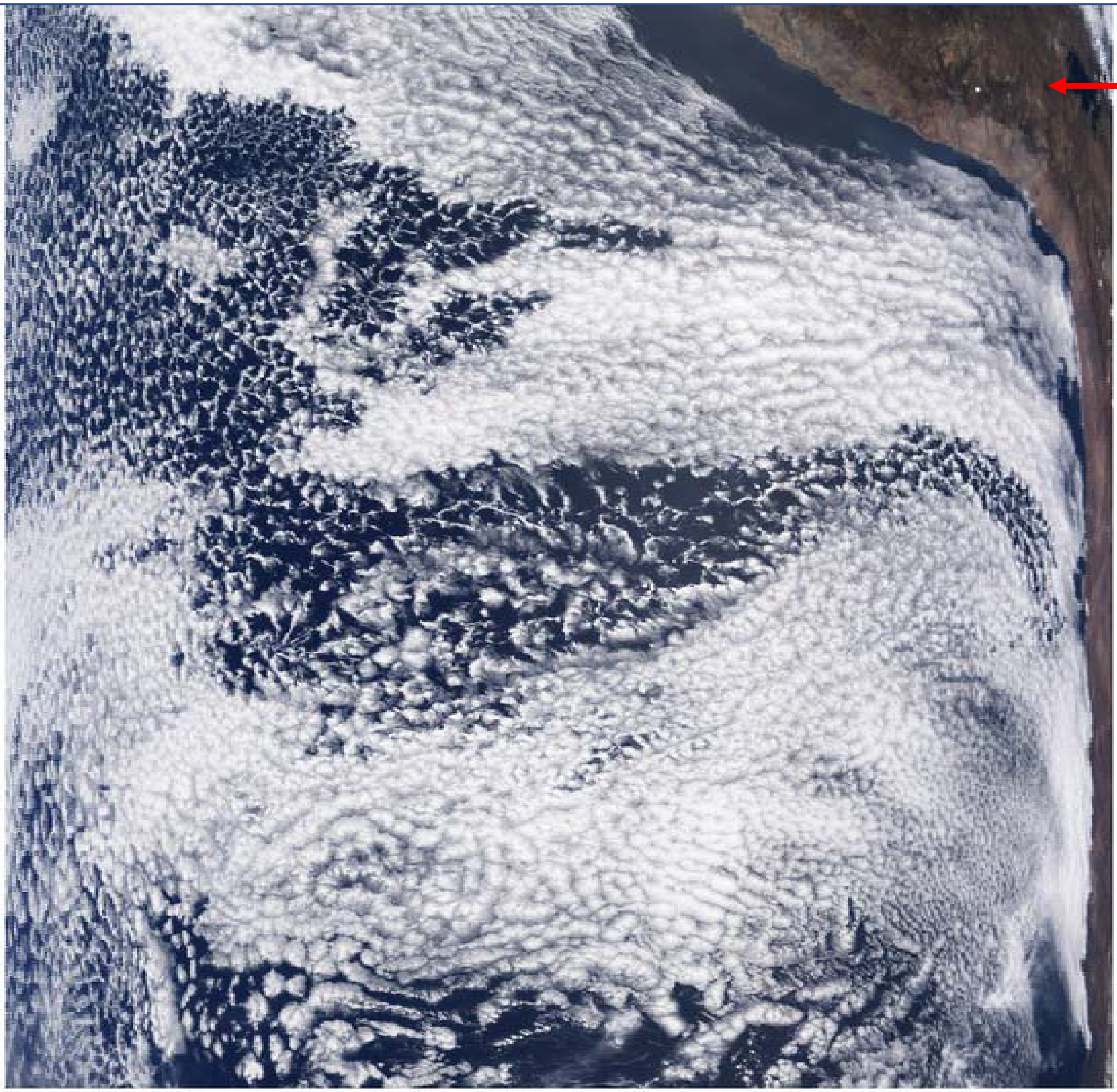


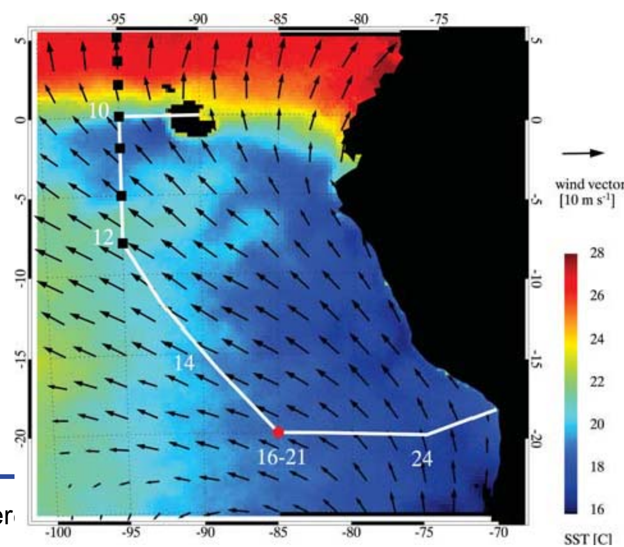
Figure 13 Schematic NE–SW cross section over the northeastern Pacific, summarizing typical observed cloud regimes. From right to left, the sea surface temperature increases and subsidence decreases. The stippled area is the PBL, the top of which is shown by the continuous and discontinuous double-stroked lines. The dashed lines above the cumulus clouds show an inversion layer, which is principally the trade wind inversion. (Redrawn from Arakawa, 1975.)

Stratocumulus … from Satellite



MODIS true color
(1540UTC, 20 Oct. 2001)

SST & surface wind



(Courtesy Martin Köhler)

Clouds are an important part of the general circulation

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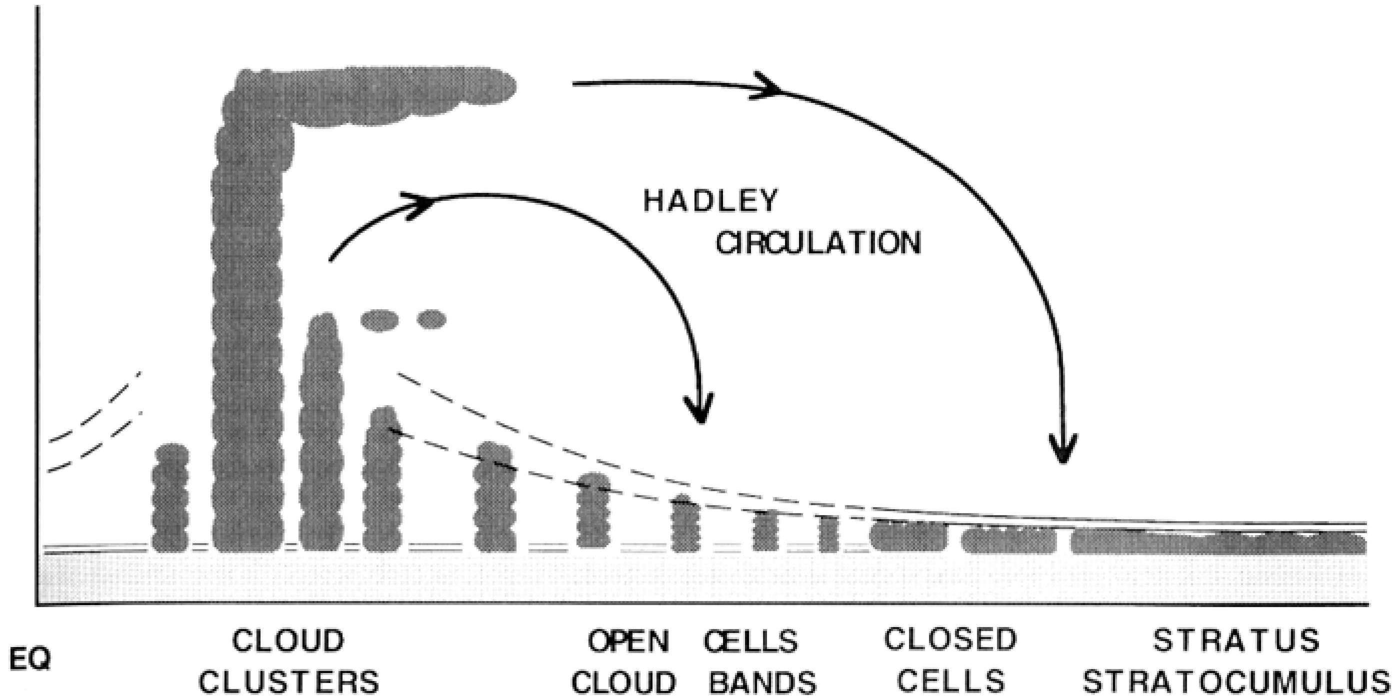

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Geographical distribution of deep convection

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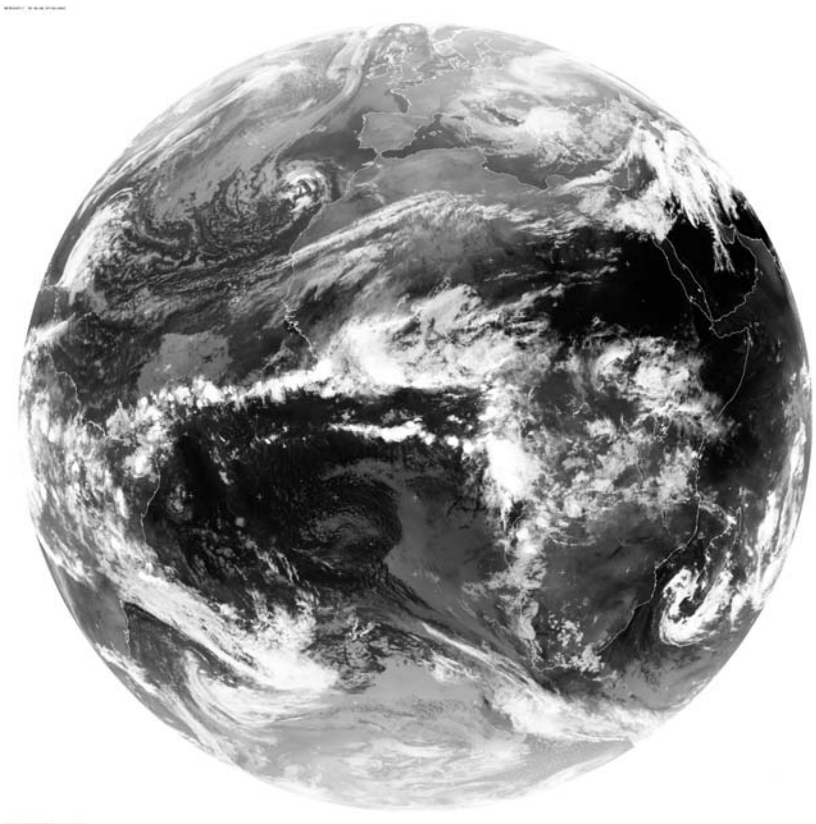
- Convection occurs where the atmosphere is most unstable
  - e.g. over warm waters, hot land (Inter-Tropical Convergence Zone – ITCZ)
  - sea-land interaction (e.g. monsoon)
  - large scale lifting (embedded convection)
    - equatorial waves
    - orographic flows
    - extra-tropical storms (baroclinic instability)

- Non convective clouds are formed through
  - large scale lifting
  - radiative cooling (e.g. fog)



IR GOES METEOSAT 7/04/2003

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Clouds formed in the extra tropics at warm/cold fronts

- Non convective clouds are typically formed as air from warm fronts is lifted over colder air

- Air lifted at cold fronts typically leads to convection

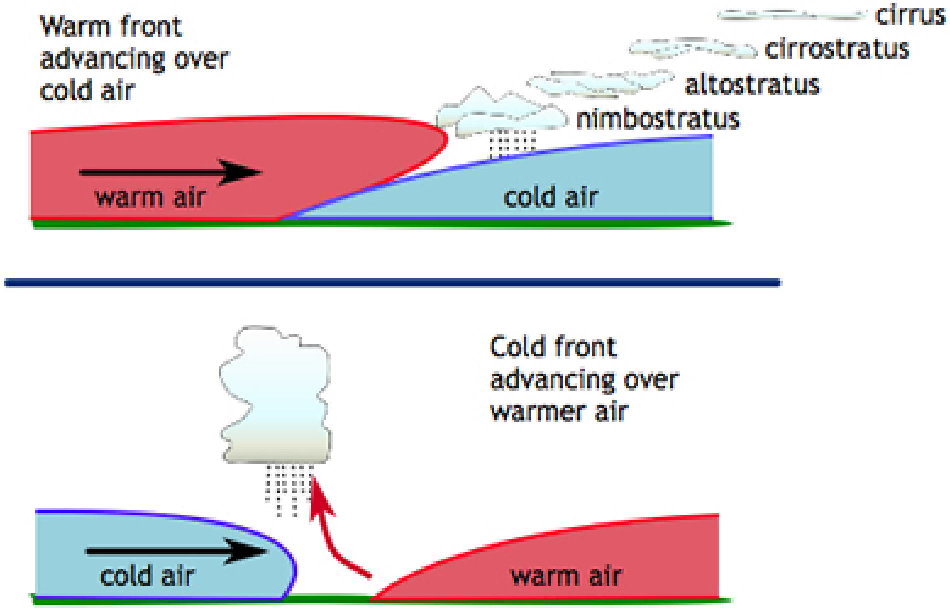

Image courtesy of Windows to the Universe

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Clouds in NWP models

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- clouds occur in different parametrizations:
  - Convection scheme (convective clouds)
    - deep convection
    - shallow convection
  - Boundary layer scheme (boundary layer clouds)
    - well mixed clouds at BL top
  - Cloud scheme (large scale clouds – non convective)
    - complex micro physics
      - liquid clouds (rain)
      - ice clouds (snow)
      - mixed phase

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Clouds in NWP models

- Dynamical interaction of clouds
  - latent heat release
    - net latent heat release $\cong$ surface precipitation
  - radiative cooling
    - cloud top cooling can be up to 7 degrees per hour
      - turbulent overturning and mixing within clouds (needs to be parametrized!)
    - cooling in clear air only about 2 degrees per day

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Parametrized clouds and model climate

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- Cloud and convection parametrizations have a strong impact on the model climate and balance relationships in the model
  - stability (temperature profile)
  - moisture content
  - height of inversions
  - etc.
- Many of these relationships are fast (i.e., the model will tend towards such balances on short time scales)

Problem for data assimilation

- The model may respond wrongly to the correct initial conditions
  - tends towards its own climate
  - “How can we initialize the model to respond correctly?”
- Bias correction
  - which part of the model bias should we try to correct? (If we knew it.)

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Some important things to keep in mind

- The temperature field is smoothed by buoyancy constraint
  - can be interpolated (e.g., to the location of an observation)
- The moisture field
  - is small scale / can have strong subgrid variations
    - interpolation very problematic
  - interaction with dynamics is strongly nonlinear (latent heat, radiative cooling)
- Clouds are an active part of the flow
  - it makes little sense to assimilate a cloud if it does not fit to the temperature and wind field
- Cloud and convection parametrizations contribute to the model climatology (which generally differs from that of the real world)

  $\longrightarrow$ Model bias

  It makes little sense to correct for model bias if it is related to a fast equilibrium

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Data assimilation in cloudy air
The challenges

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- How to ....
  - make sure observations are not contaminated by clouds?
    - cloud screening
    - “subtracting” cloud impact from the measurements
  - get cloud information from the observations?
  - profit from cloud information for improving the weather forecast?

- Problems and answers generally differ for different DA systems
  - variational DA (1D Var, 3D Var, 4D Var, ..)
  - Ensemble methods (Kalman Filter, ..)

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Observation operators

- Both Ensemble KF and Var need observation operators

$$J(x) = \frac{1}{2}(x - x_b)^T \boldsymbol{B}^{-1}(x - x_b) + \frac{1}{2}(y - y_{mod})^T \boldsymbol{R}^{-1}(y - y_{mod})$$

y : observation

$y_{mod} = H(x)$

H : *generalized* observation operator

Example 4D Var:

$$H(x) = H_{obs} \cdot S[M(x)]$$

M : time evolution operator (NWP model)

S : interpolation to observation location

H_{obs} : classical observation operator

$H_{obs}(\mathbf{x}) \rightarrow y_{mod}$

$H_1(\mathbf{x}) \rightarrow \tilde{\mathbf{x}}$ physics operator

$RTTOV(\tilde{\mathbf{x}}) \rightarrow y_{mod}$ radiative transfer model

y_{mod} : model observations

$\mathbf{x}$: standard model variables (changed by assimilation)

$\tilde{\mathbf{x}}$: standard model variables + cloud variables: e.g., C_{fr}, p_{cldtop}

Ensemble KF vs Var

- Both need observation operators

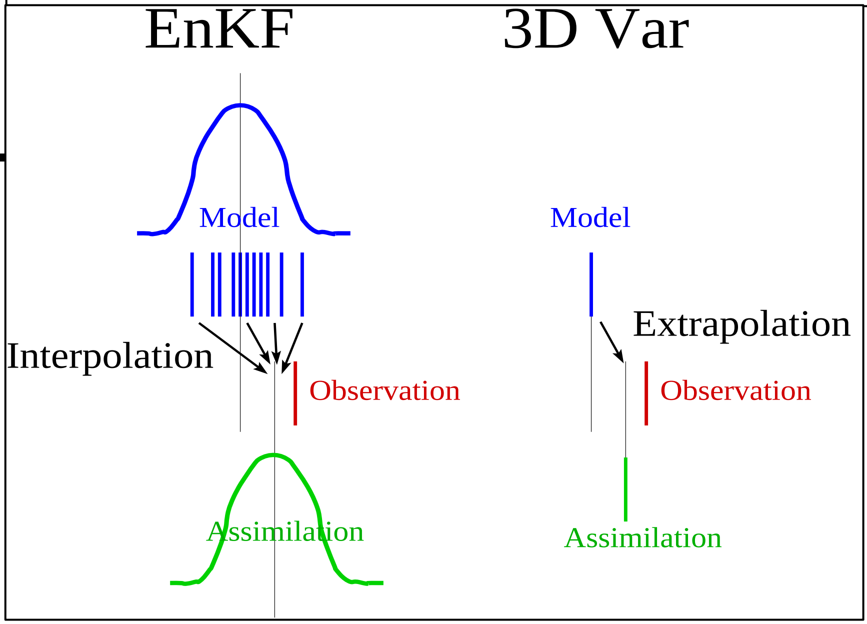
$$H_{obs}(\mathbf{x}) \rightarrow y_{mod}$$

$$H_1(\mathbf{x}) \rightarrow \tilde{\mathbf{x}} \quad \text{physics operator}$$
$$RTTOV(\tilde{\mathbf{x}}) \rightarrow y_{mod} \quad \text{radiative transfer model}$$

  - Var also needs linear and adjoint obs operator

  ⟶ obs operator needs to be very robust and smooth

- 3D Var extrapolates (uses tangent)
- EnKF also interpolates (uses secant)



  - EnKF uses a secant (not a tangent)
  - Var can make several outer loops

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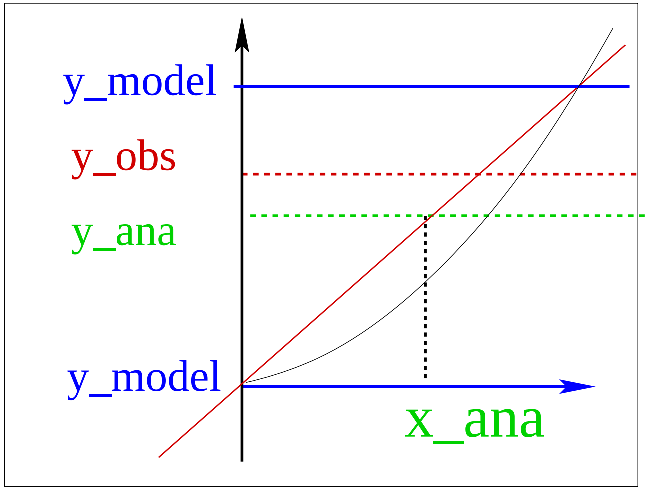
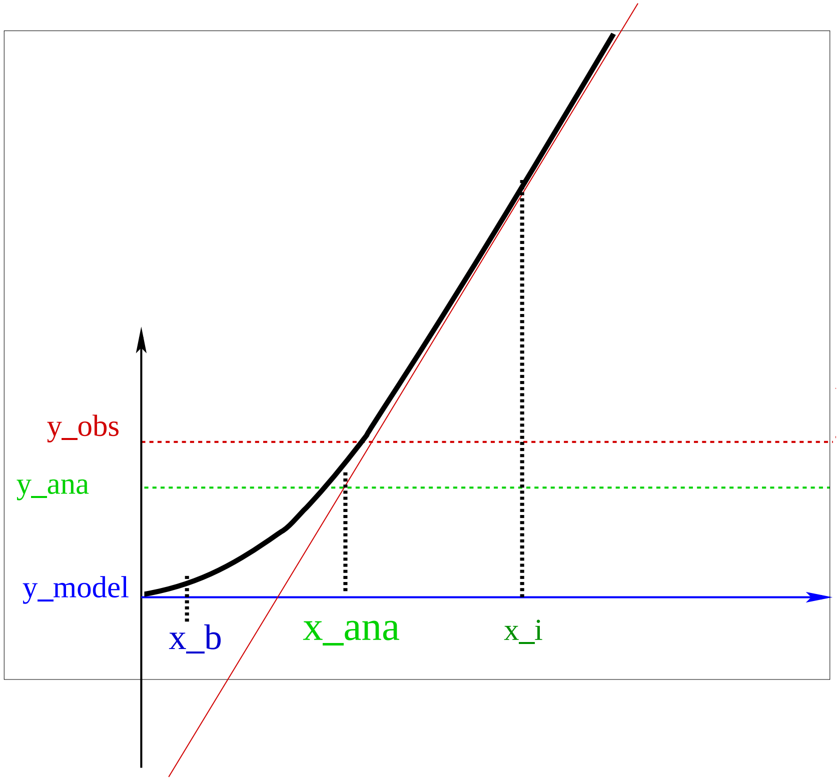
Ensemble KF vs Var

- EnKF uses a secant (not a tangent)
- Var can make several outer loops





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Ensemble KF vs Var for convective scales

- Var extrapolates
  - Can a strongly nonlinear object be found by extrapolation?

- EnKF has limited ensemble size
  - localized features (like thunderstorms or cloud top height, etc.) will probably not be matched precisely by any ensemble member
  - What do you do when thunderstorm is only approximately in the right position? Or cloud top height is only approximate?
  - Does a linear combination of ensemble members with different thunderstorms (at different positions, etc.) give a dynamically consistent thunderstorm?

- Strategie: Do not ask for too much:
  - e.g. assimilate only one moisture variable (on top of the other variables) to make regions moister or drier depending on observations
    - total water: qt=qv+qc (Met Office, UK)

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Cloud screening

- DWD currently only assimilates radiances which are "cloud free"
- Screening methods use channels of the respective satellite instruments

- MW
  - is field of view (FOV) perturbed by too much cloud water?
  - AMSU A (temperature sensitive channels)

combination of AMSU A channels → FOV perturbed by cloud ??

  - AMSU B (humidity sensitive channels)

combination of AMSU B channels → FOV perturbed by cloud ??

Cloud screening

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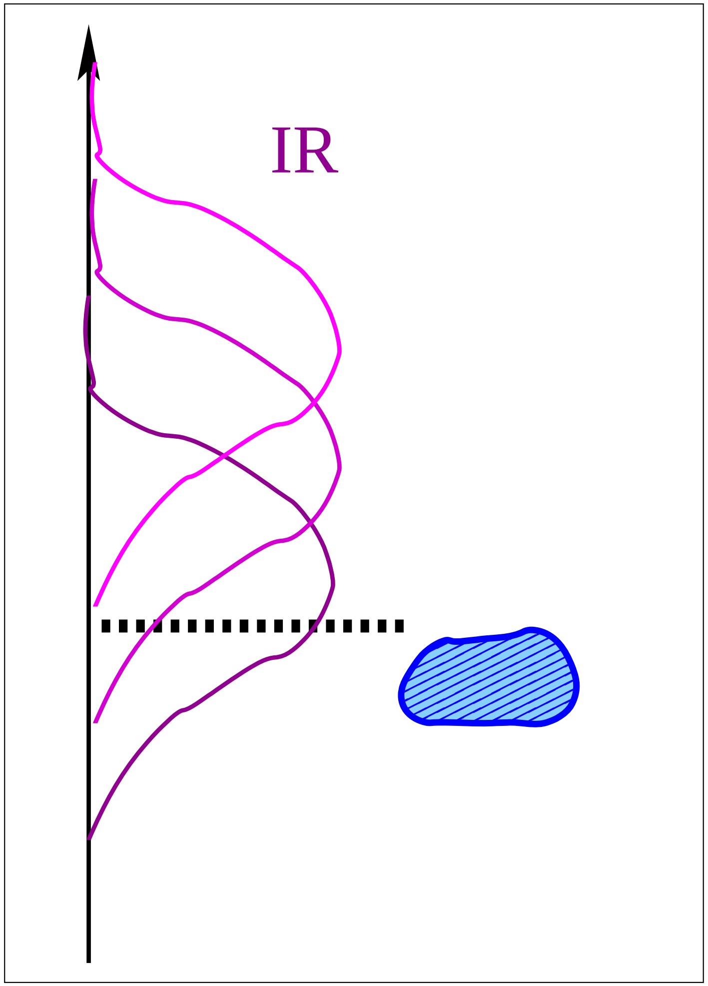
- IR
  - HIRS, IASI and AIRS
    - get as close to the cloud as you can
    - use First Guess Departures
      FGD = obs - fg
      (i.e. include model info)
      to identify cloudy fingerprint
  - HIRS (20 Channels, 8 C02 channels)
    - screening criterion:

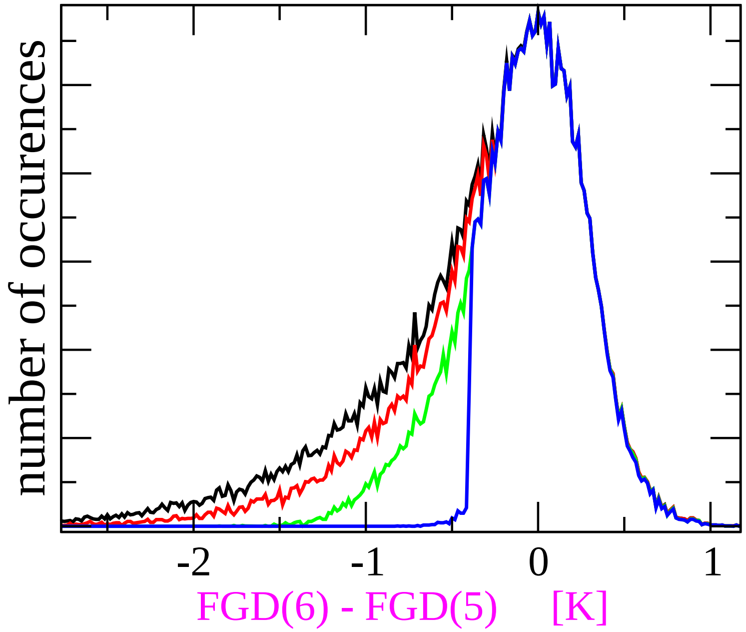
      $FGD_n - FGD_{n-1}$ < Thresh.

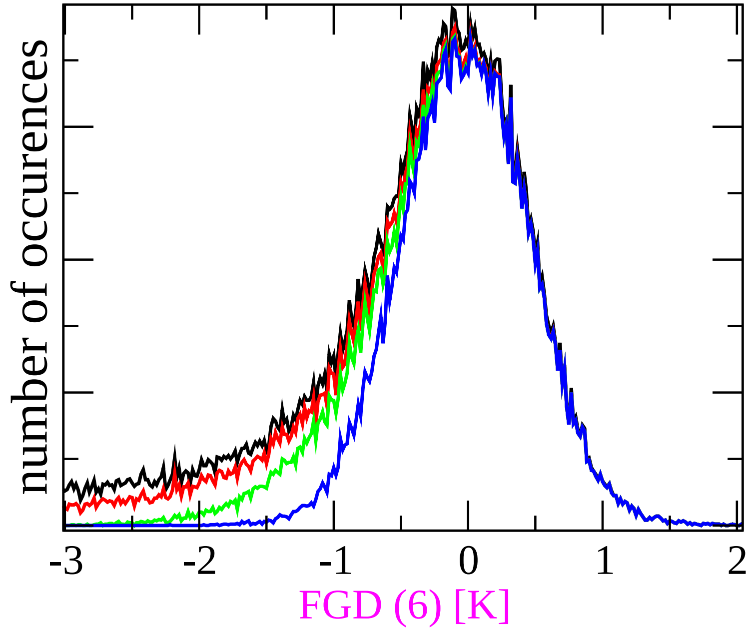


Example: Cloud screening
HIRS (chan. 6, middel/lower troposphere)

$FGD_n - FGD_{n-1}$ < Thresh.

- Cloud screening
  - makes PDF more Gaussian
  - induces bias

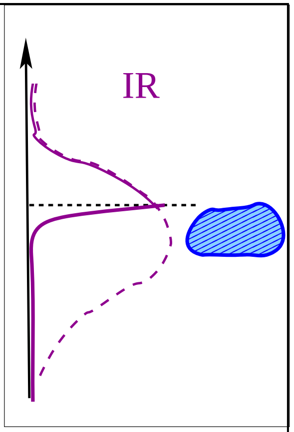




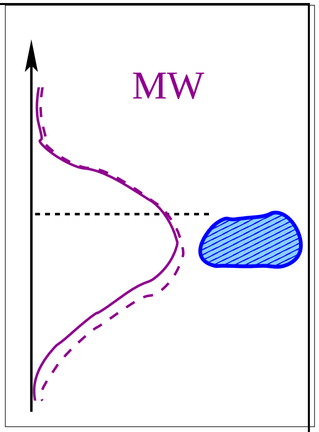
Assimilation of cloudy radiances

- Satellite radiances are assimilated mainly in the infrared (IR) and microwave (MW) band

- IR
  - strongly nonlinear (opaque)
  - good identification of cloud location
  - more than 80% of channels are affected by cloud
  - cloud impact on IR sounders is subtracted from RT computations.



- MW
  - multiple scattering important
  - sees only thick clouds and rain
  - less than 20% of channels are affected by cloud
  - cloud information from MW imagers is assimilated



- Some work in the "near IR" and visible regime is carried out by the Ertel Center for DA in Munich

Assimilation of cloud affected satellite radiances
What has been done?

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What has been done?

- MW imagers,
  - ECMWF
  - all sky approach
  - long development route.
    - 2005-2009 only:
      - 1D+4D Var
      - TCWV as pseudo-observation
  - bias correction with "symmetric" cloud variable as predictor
  - screening out *low-skill situations*
    - cold air outbreaks
    - intense tropical convection

$$H(\mathbf{x}) \rightarrow y_{mod}$$

$$H_1(\mathbf{x}) \rightarrow \tilde{\mathbf{x}} \quad \text{physics operator}$$

$$RTTOV(\tilde{\mathbf{x}}) \rightarrow y_{mod} \quad \text{radiative transfer model}$$

y_{mod} : model observations

$\mathbf{x}$: standard model variables (changed by assimilation)

$\tilde{\mathbf{x}}$: standard model variables + cloud variables : C_{fr}, p_{cldtop}

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Assimilation of cloud affected satellite radiances
What has been done?

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What has been done?

- IR sounders, HIRS, AIRS,IASI
  - ECMWF
  - only fully overcast situations
  - only RT operator
    - cloud variables:
      - first guess estimated from independent observations (model first guess not good enough)
      - optimized through additional term to the cost function
      - not used for updating model state

$$H(\mathbf{x}) \rightarrow y_{mod}$$

~~$H_1(\mathbf{x}) \rightarrow \tilde{\mathbf{x}}$ physics operator~~

$RTTOV(\tilde{\mathbf{x}}) \rightarrow y_{mod}$ radiative transfer model

y_{mod}	:	model observations
$\mathbf{x}$	:	standard model variables (changed by assimilation)
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Assimilation of cloud affected satellite radiances
What has been done?

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What has been done?

- IR sounders, HIRS, AIRS,IASI
  - Met Office, UK
  - only radiances affected less than 10%
  - only RT operator
    - cloud variables:
      - first guess estimated from independent observations (model first guess not good enough)
      - optimized through 1D Var step
      - not used for updating model state

$$H(\mathbf{x}) \rightarrow y_{mod}$$

~~$H_1(\mathbf{x}) \rightarrow \tilde{\mathbf{x}}$ physics operator~~

$RTTOV(\tilde{\mathbf{x}}) \rightarrow y_{mod}$ radiative transfer model

y_{mod} : model observations

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Assimilation of cloud affected satellite radiances
What has been done?

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$$H(\mathbf{x}) \rightarrow y_{mod}$$

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$$RTTOV(\tilde{\mathbf{x}}) \rightarrow y_{mod} \quad \text{radiative transfer model}$$

y_{mod} : model observations
$\mathbf{x}$: standard model variables (changed by assimilation)
$\tilde{\mathbf{x}}$: standard model variables + cloud variables : C_{fr}, p_{cldtop}

- IR sounders, AIRS
  - Meteo France
  - only
    - Stratospheric and upper-tropospheric radiances
    - lower-troposheric clouds
  - only RT operator
    - cloud variables:
      - first guess estimated from independent observations (model first guess not good enough)
      - "CO2 slicing method" (popular retrieval method – not explained in this lecture)
      - not used for updating model state

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Assimilation of cloud retrievals
What has been done?

- Met Office, limited area model

  - convert cloud fraction (0%-100%) into total relative humidity

  - use filter to switch off assimilation if
    - C.fract.(obs)=C.fract.(model)=0

  or C.fract.(obs)=C.fract.(model)=1

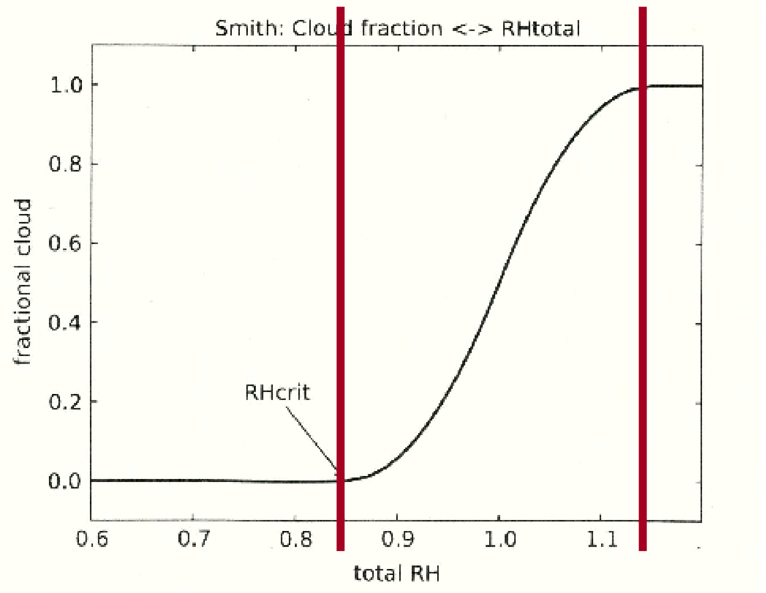

Figure 1. Relationship between total relative humidity and cloud fraction defined by Smith (1990), with $RH_{crit} = 0.85$.

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Assimilation of cloud retrievals
What has been done?

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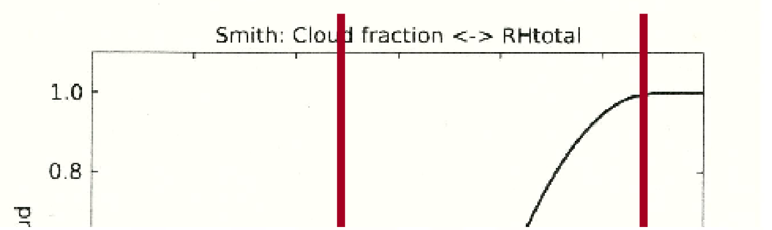
- Met Office, limited area model

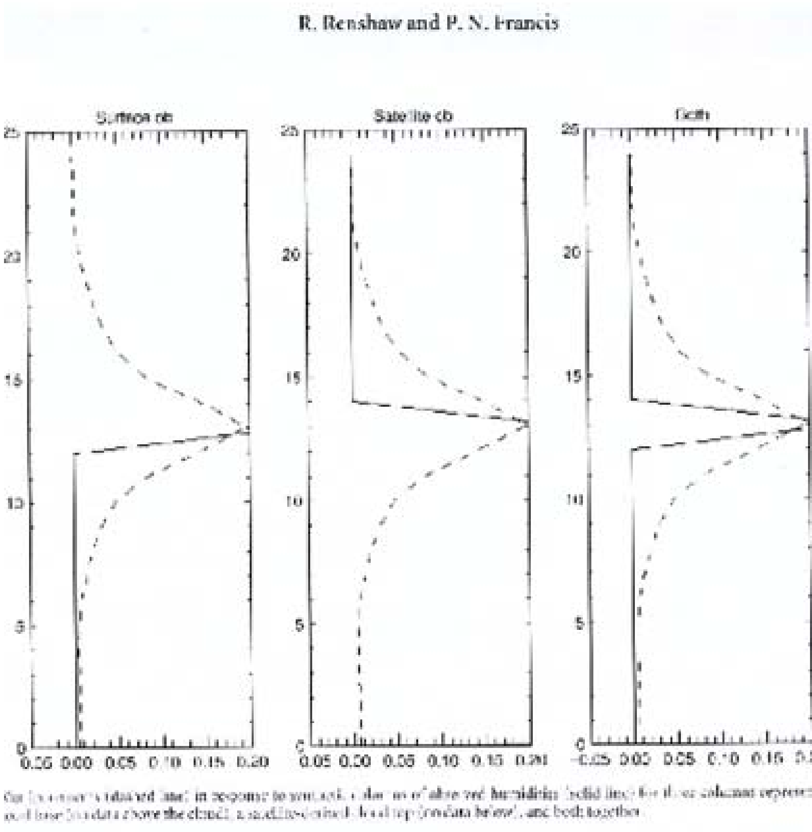
  - convert cloud fraction (0%-100%) into total relative humidity

  - use filter to switch off assimilation if
    - C.fract.(obs)=C.fract.(model)=0

    or C.fract.(obs)=C.fract.(model)=1

  - but:
    - use ***cloud-free information*** above and below clouds (if available)





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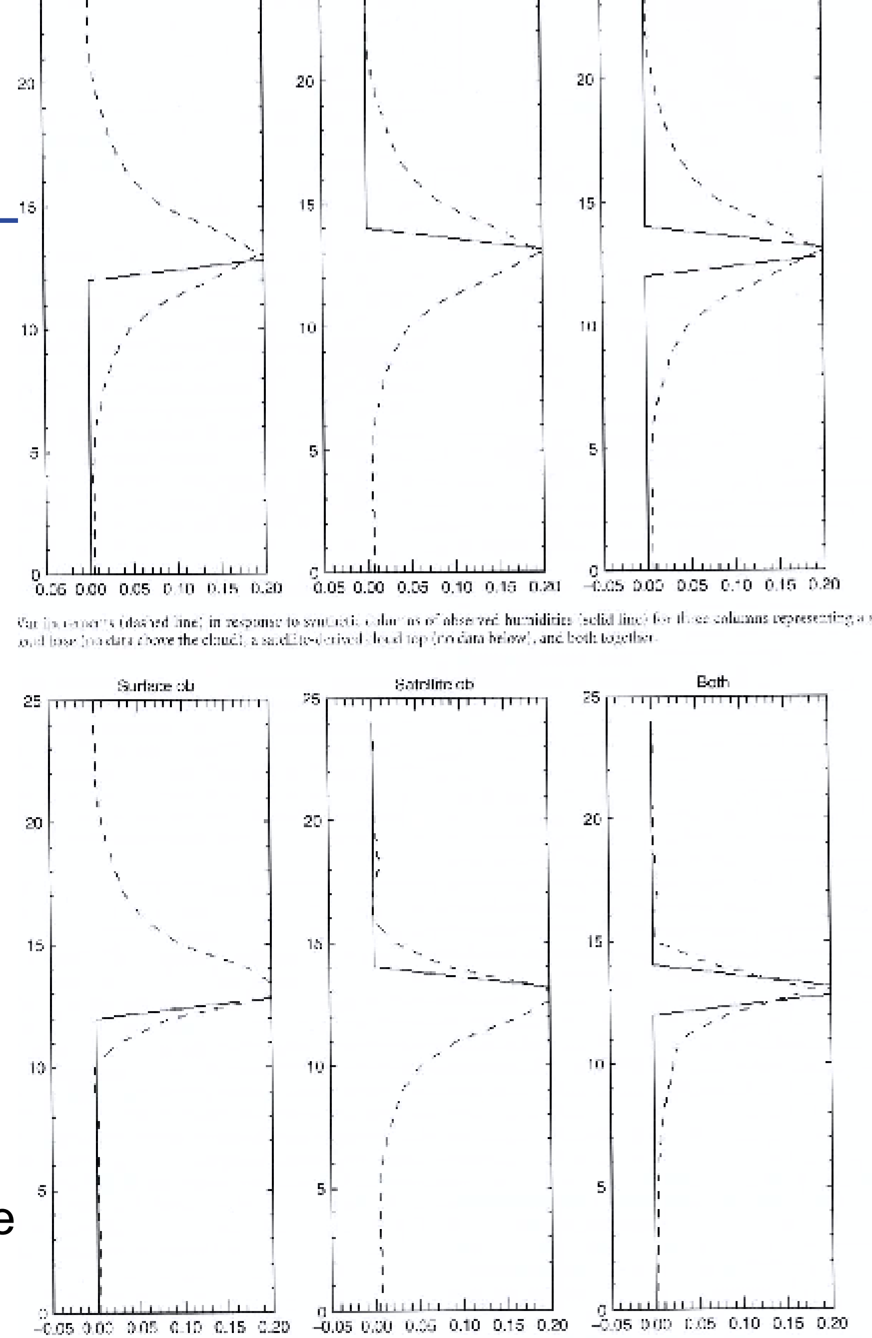
Assimilation of cloud retrievals
What has been done?

- Met Office, limited area model
  - convert cloud fraction (0%-100%) into total relative humidity
  - use filter to switch off assimilation if
    - C.fract.(obs)=C.fract.(model)=0

    or C.fract.(obs)=C.fract.(model)=1
  - but:
    - use ***cloud-free information*** above and below clouds (if available



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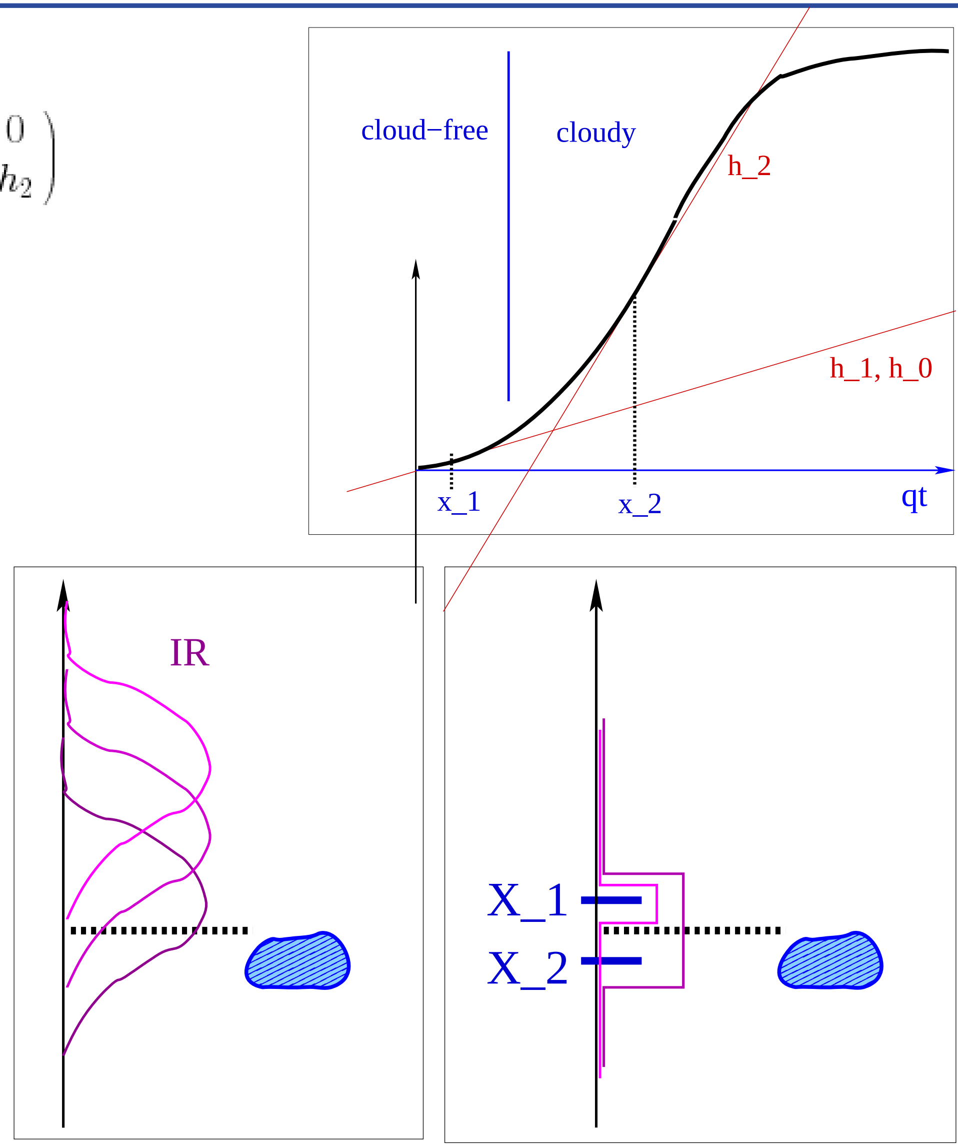
A simplified model problem

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

$$\mathcal{H}(x) = \mathcal{H}(\hat{x}) + \boldsymbol{H}\,(x - \hat{x})\ ; \qquad \boldsymbol{H} = \begin{pmatrix} h_1 & 0 \\ h_0 & h_2 \end{pmatrix}$$

$$\boldsymbol{R} = \begin{pmatrix} r_1 & 0 \\ 0 & r_2 \end{pmatrix}, \qquad \boldsymbol{B} = \begin{pmatrix} b_1 & b_0 \\ b_0 & b_2 \end{pmatrix}$$



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A simplified model problem

$$\mathcal{H}(x) = \mathcal{H}(\hat{x}) + \boldsymbol{H}\,(x - \hat{x})\;; \qquad \boldsymbol{H} = \begin{pmatrix} h_1 & 0 \\ h_0 & h_2 \end{pmatrix}$$

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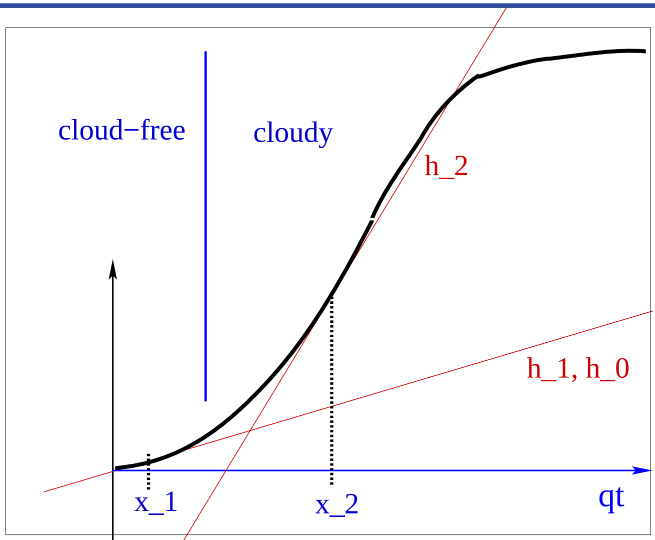
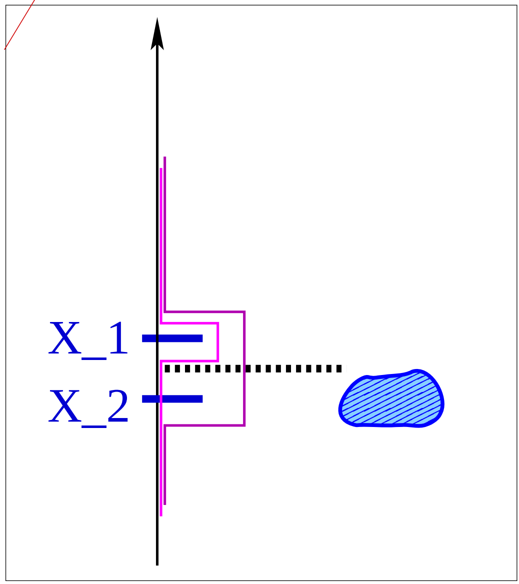
$$\begin{pmatrix} \Delta_a y_1 \\ \Delta_a y_2 \end{pmatrix} \equiv H\,(x - x_b) = \begin{pmatrix} \Lambda_1^{-1} & 0 \\ 0 & \Lambda_2^{-1} \end{pmatrix} \begin{pmatrix} 1 & \gamma_{2\to 1} \\ \gamma_{1\to 2} & 1 \end{pmatrix} \begin{pmatrix} \Delta y_1 \\ \Delta y_2 \end{pmatrix}$$

$$(x - x_b) = \boldsymbol{K}\,\{y - \mathcal{H}(x_i) - H\,(x_i - x_b)\}$$

$$\begin{pmatrix} \Delta y_1 \\ \Delta y_2 \end{pmatrix} = y - \mathcal{H}(x_i) - H\,(x_i - x_b)$$





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A simplified model problem

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$$R_1 = \frac{r_1}{b_1 h_1^2} \qquad R_2 = \frac{r_2}{b_2 h_2^2}$$

$$\widehat{h}_0 = \frac{h_0}{h_2}\sqrt{\frac{b_1}{b_2}}$$

$$\hat{b}_0 = \frac{b_0}{\sqrt{b_1 b_2}}$$

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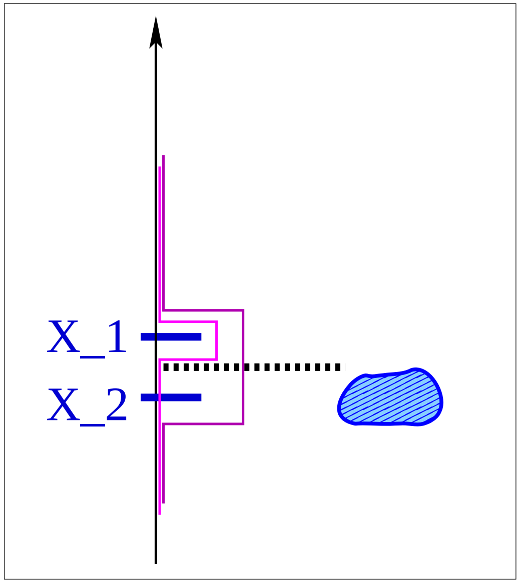
$$\Lambda_1 = 1 + R_1\left\{1 + \frac{(\widehat{h}_0 + \hat{b}_0)^2}{[1-\hat{b}_0^2] + R_2}\right\}$$

$$\Lambda_2 = 1 + R_2 \frac{\left\{1 + \frac{(\widehat{h}_0 + \hat{b}_0)^2}{[1-\hat{b}_0^2] + (1+\widehat{h}_0^2 + 2\hat{b}_0\widehat{h}_0)R_1}\right\}}{(1+\widehat{h}_0^2 + 2\hat{b}_0\widehat{h}_0)}$$

$$\gamma_{2\to 1} = \frac{(\widehat{h}_0 + \hat{b}_0)}{[1-\hat{b}_0^2] + R_2} R_1 \frac{h_1\sqrt{b_1}}{h_2\sqrt{b_2}}$$

$$\gamma_{1\to 2} = \frac{(\widehat{h}_0 + \hat{b}_0)}{[1-\hat{b}_0^2] + (\widehat{h}_0^2 + 2\hat{b}_0\widehat{h}_0 + 1)\,R_1} R_2 \frac{h_2\sqrt{b_2}}{h_1\sqrt{b_1}}$$



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A simplified model problem

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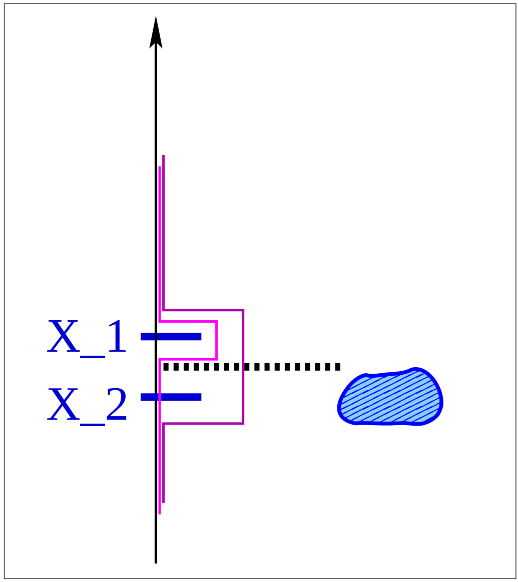
$$\Lambda_2 = 1 + R_2 \frac{\left\{ 1 + \frac{\left(\widehat{h}_0 + \hat{b}_0\right)^2}{\left[1 - \hat{b}_0^2\right] + \left(1 + \widehat{h}_0^2 + 2\hat{b}_0 \widehat{h}_0\right) R_1} \right\}}{\left(1 + \widehat{h}_0^2 + 2\hat{b}_0 \widehat{h}_0\right)}$$

$$\gamma_{2\to 1} = \frac{\left(\widehat{h}_0 + \hat{b}_0\right)}{\left[1 - \hat{b}_0^2\right] + R_2} R_1 \frac{h_1\sqrt{b_1}}{h_2\sqrt{b_2}}$$

$$\gamma_{1\to 2} = \frac{\left(\widehat{h}_0 + \hat{b}_0\right)}{\left[1 - \hat{b}_0^2\right] + \left(\widehat{h}_0^2 + 2\hat{b}_0 \widehat{h}_0 + 1\right) R_1} R_2 \frac{h_2\sqrt{b_2}}{h_1\sqrt{b_1}}$$



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Assimilation in cloudy air
Topics (check list)

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- Impact on the model state
  - Which variables are we trying to alter?
    - (only T? Also qv? Even qc?)
- Scene selection
  - Which type of cloud affected radiance do we want to process (assimilate)?
- First guess
  - Is the model first guess good enough for cloud parameters?
- How are errors affected by the presence of clouds?:
  - Observation errors?
  - Bias correction?
    - How to deal with error characteristics / biases in cloudy areas?
- Foreward operators
  - physics operators / RT model
  - nonlinear / linear / adjoint
- Additional quality control
  - screening (excluding) situations where method has problems (e.g. first guess too bad)

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Questions? Remarks?

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