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**Diurnal variations of  
water in the tropical  
upper troposphere**

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# Diurnal variations of humidity and ice water content in the tropical upper troposphere

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## Abstract

Observational results of diurnal variations of humidity from Odin-SMR and AURA-MLS, and cloud ice mass from Odin-SMR and CloudSat are presented for the first time. Comparisons show that the retrievals of humidity and cloud ice from these three satellite instruments are in good agreement. The retrieved data are combined from four almost evenly distributed times of the day allowing mean values, amplitudes and phases of the diurnal variations around 200 hPa to be estimated. This analysis is applied to six climatologically distinct regions, five located in the tropics and one over the subtropical northern Pacific Ocean. The strongest diurnal cycles are found over tropical land regions, where the amplitude is in the order of 6 %RH<sub>i</sub> for humidity and 50% for ice mass. The greatest ice mass is for these regions found during the afternoon, and the humidity maximum is observed to lag this peak by ~6 h. Over tropical ocean regions the variations are smaller and the maximum in both ice mass and humidity are found during the early morning. Observed results are compared with output from three climate models (ECHAM, EC-EARTH and CAM3). Direct measurement-model comparisons were not possible because the measured and modelled cloud ice masses represent different quantities. To make a meaningful comparison, the amount of snow had to be estimated from diagnostic parameters of the models. There is a high probability that the models underestimate the average ice mass (below the 1- $\sigma$  uncertainty). The models show also clear deficiencies when it comes to amplitude and phase of the regional variations, but to a varying degree.

## 1 Introduction

Atmospheric water vapour is the dominant greenhouse gas in the Earth's atmosphere, and the amount and distribution will respond to changes in temperature, micro-physical processes, and atmospheric circulation (IPCC, 2007). Humidity changes in the tropical upper troposphere are of particular concern, since they are less well understood and

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have a stronger top of the atmosphere radiative impact than for other regions of the atmosphere (Held and Soden, 2000). Tropical upper tropospheric ice clouds, intimately connected to the water vapour, also have a strong top of the atmosphere radiative impact (Harries, 2000). Thus, in order to accurately predict the future climate of Earth, it is important to understand the processes which control the water budget and determine the distribution of water vapour and clouds in the tropical upper troposphere.

Remote sensing measurements from satellites provide a useful tool for understanding atmospheric processes and evaluating climate model simulations. There have been several measurement studies of the diurnal cycle of tropical convective clouds and humidity. Most of these studies are based on geostationary infrared (IR) data, but also combinations of IR and radar data from Tropical Rainfall Measuring Mission (Hong et al., 2006; Liu and Zipser, 2008a) as well as IR and passive microwave measurements (Zelinka and Hartmann, 2009) have been used. Typically, IR brightness temperatures at  $6.7\ \mu\text{m}$  are used to estimate clear sky humidity in the upper troposphere (200–500 hPa), and various thresholds of the  $11\ \mu\text{m}$  window channel are used to estimate occurrence frequencies of various cloud types (e.g. deep convective clouds  $T_{11} < 220\ \text{K}$ , and cirrus anvils clouds  $220\ \text{K} < T_{11} < 260\ \text{K}$ ). It has been demonstrated that a noticeable diurnal cycle of both deep convective clouds, high cold clouds, and upper tropospheric humidity (UTH) is present over land and ocean regions associated with convective activity (Hong et al., 2006; Chung et al., 2007). The UTH is observed to lag the peak of high cloud cover by several hours which, in turn, lags the peak of deep convective cloud occurrence. It is critical to understand whether deep convection serves to moisten the upper troposphere through the evaporation of the cirrus anvil clouds generated by deep convection as suggested by Tian et al. (2004), or that the moistening results from the same dynamical mechanisms responsible for the formation and maintenance of the cirrus anvil, as suggested by Soden (2004). The consensus seems to be the latter (IPCC, 2007), however, if micro-physical, rather than large scale advective processes, are more important for the moistening, confidence in climate model simulations of the water vapour feedback decreases. This is because the confidence in

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climate model simulations of micro-physical processes is low (IPCC, 2007).

Satellite IR sensors provide only an indirect estimate of the properties of deep convective clouds because they primarily observe cloud top temperatures (Garrett et al., 2009), and provide little or no information of the interior of the clouds. Additionally, humidity can only be retrieved for cloud free conditions (Soden and Bretherton, 1993). Thus, this type of instrument is not optimal for studying the diurnal cycle of the upper tropospheric water budget.

This paper focuses on studying the diurnal cycle of upper tropospheric water by combining measurements from three sensors operating in the mm and sub-mm part of the wavelength spectrum. Odin-SMR (Murtagh et al., 2002) and AURA-MLS (Waters et al., 2006) provide measurements of humidity for both clear and cloudy sky conditions. CloudSat (Stephens et al., 2002) and Odin-SMR (Eriksson et al., 2007, 2008; Rydberg et al., 2009) provide measurements of cloud ice mass. The measured signals by CloudSat and Odin-SMR are related to the amount of cloud ice mass in the clouds. All three instruments are placed in polar sun-synchronous orbits with tropical local observation times of 01:40 a.m. and p.m. for CloudSat and AURA-MLS, and 06:00 a.m. and p.m. for Odin-SMR. The atmospheric layer considered here is approximately centred around 200 hPa. A practical reason for studying this particular layer is because of the Odin-SMR systematic uncertainties are smallest for this layer (Ekström et al., 2007). Consequently, the focus is somewhat higher in the atmosphere than previous UTH studies. This is the altitude region where the ice water content is the highest, in relative terms, with respect to the total water mass (Ekström and Eriksson, 2008).

Differences in night and daytime observations of cloud and water vapour have been reported from CloudSat (Liu and Zipser, 2008b) and AURA-MLS (Liu and Zipser, 2009) observations. In addition the CloudSat and AURA-MLS ice mass products have been compared with climate model output (Waliser et al., 2009; Wu et al., 2009), although the ice mass diurnal cycle was not within the scope of the studies.

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Therefore, a combination of water products from Odin-SMR, AURA-MLS, and Cloud-Sat offers a unique possibility to study the diurnal variations of the water budget in the upper troposphere. As these polar orbiting satellites do not allow us to follow the time evolution of individual convective systems, the climatology of the water in the tropical upper troposphere is studied. Climatological means from each instrument provide four almost evenly distributed values during the day allowing to study the mean and the diurnal amplitude and phase of water variations in the upper tropical troposphere.

A second objective of this paper is to evaluate whether three climate models (EC-EARTH, ECHAM, and CAM3) are capable of realistically capturing the diurnal variation of water in the tropical upper troposphere, as observed by the combination of satellite instruments. To build confidence in climate models' ability to accurately project future climate it is desirable to evaluate the model performance at various shorter timescales through comparison with appropriate measurements (IPCC, 2007). In the tropics the solar diurnal cycle is one of the basic forcing modes of the climate system and, as such, a climate model's response to this forcing should be a key test of the physical parameterisations used in the model (Slingo et al., 2003). Particularly over tropical land, accurate simulation of the diurnal cycle in the atmosphere is critical for the realistic simulation of the water and energy budget at the Earth's surface (Yang and Slingo, 2001). Model simulated diurnal variability of several parameters have previously been compared with various measurements, (e.g. Dai and Trenberth, 2004; Tian et al., 2004). These comparisons found that models had difficulty in reproducing the mean, amplitude and diurnal phase of parameters related to upper tropospheric water, such as UTH and cloud cover. The novelty of the comparison shown here is the unique combination of satellite measurements to determine the diurnal variation and the fact that the diurnal cycle of ice water content is included for the first time.

## 2 Data

### 2.1 Odin-SMR

#### 2.1.1 Observations

The Odin satellite was launched in February 2001 into a 600 km quasi-polar sun-synchronous orbit with an ascending node around 18:00 h local time. The payload includes the first space-borne sensor for atmospheric sub-mm observations, Odin-SMR. This limb sounding instrument measures thermal emission at frequencies around 500 GHz. The atmospheric signal is recorded through a 1.1 m telescope, single-sideband heterodyne receivers, and two auto-correlation spectrometers with 800 MHz bandwidth. Further information can be found in Murtagh et al. (2002) and Ekström et al. (2007).

Odin's observation time has been time-shared between astronomy, stratospheric, and mesospheric modes. The retrievals of upper tropospheric ice water content (IWC) and relative humidity w.r.t. ice (RHi) considered are based on radiances collected by the stratospheric mode of Odin-SMR from the time period 2002–2009.

#### 2.1.2 Retrieval approach

The retrieval of upper tropospheric IWC and RHi is not a part of the operational retrievals of Odin-SMR. The retrieval is obtained from a Bayesian retrieval algorithm described in Rydberg et al. (2009). The retrieval approach is based on a retrieval database, consisting of atmospheric states and simulated radiances. The atmospheric states in the retrieval database are created based on existing relevant a priori data, where cloud structure information from CloudSat and weather information are incorporated. However, relevant a priori data on the variability of tropical ice cloud particle size distribution (PSD) parameters were considered to be lacking. A main assumption made while generating the atmospheric states is that the PSD derived by McFarquhar

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and Heymsfield (1997) describe the tropical mean PSD.

Retrieved profiles of IWC and RHi are a weighted mean of the states in the retrieval database. Only retrievals from around 13 km in altitude are considered here. The vertical resolution is  $\sim 5$  km, and the horizontal resolution is  $\sim 2 \times 45$  km<sup>2</sup>.

5 The retrieval precision is better than 17 %RHi for RHi and  $\sim 65\%$  for IWC. The accuracy is estimated to be better than 30 %RHi for RHi (worst case estimate) and 40% for IWC ( $1-\sigma$ ).

## 2.2 CloudSat

### 2.2.1 Observations

10 CloudSat is a satellite designed to measure the vertical structure of clouds from space (Stephens et al., 2002). The satellite has a 13:40 h local time ascending node, sun-synchronous orbit at 705 km altitude. CloudSat carries a 94 GHz, 0.16° off-nadir-looking Cloud Profiling Radar which measures the power back-scattered by clouds as a function of distance from the radar. The standard data product consists of 125  
15 vertical bins that are 240 m thick, while the vertical resolution of the radar is approximately 500 m. Each profile is generated over a 160 ms integration time with a 6 dB footprint resolution of approximately 1.3 km across-track and 1.7 km along track. The minimum detectable equivalent radar reflectivity is approximately  $-30$  dBZ and the dynamic range is 70 dBZ. 2B-Geoprof radar reflectivity profiles from 2006–2009 are considered.  
20

### 2.2.2 Retrieval approach

The official CloudSat IWC product is not considered. Instead retrievals of IWC are performed in an alternative way, to match with IWC retrievals from Odin-SMR. That is, the same PSD assumptions as for Odin-SMR retrievals is applied for IWC retrievals from  
25 the official 2B-Geoprof radar reflectivity profiles and ECMWF-aux temperature profiles

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as described in Eriksson et al. (2008). The reason for using this alternative retrieval approach is to not confuse the diurnal cycle signal with different PSD assumptions, when combining Odin-SMR and CloudSat IWC retrievals.

## 2.3 AURA-MLS

### 2.3.1 Observations

AURA-MLS is a passive instrument consisting of seven radiometers operating at five spectral bands from near 118 GHz to 2.5 THz (Waters et al., 2006), although only data from three radiometers are considered here (two near 118 and one near 190 GHz). The two 118 GHz receivers at orthogonal polarisations are single sideband, while the 190 GHz receiver is double sideband. Atmospheric signals for the 118- and 190-GHz radiometers are collected by a three-reflector offset antenna system that vertically scans the limb. The primary mirror dimension is 1.6 m projected in the vertical direction at the limb tangent point. The Aura satellite has a 13:40 h ascending node sun-synchronous orbit at 705 km altitude. Version 2.2 RHi retrievals from 2004 to 2007 are considered.

### 2.3.2 Retrieval approach

The retrieval process uses an iterative scheme in an optimal estimation framework (Livesey et al., 2006). Humidity and temperature profiles are retrieved from the the 183 GHz water vapour line and 118 GHz oxygen line, respectively. Relative humidity profiles are retrieved from combining temperature and humidity retrievals. The vertical resolution is  $\sim 5$  km and the estimated  $2\text{-}\sigma$  accuracy and precision are  $\sim 35\%$  RHi and  $45\%$ , respectively (Read et al., 2007).

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## 2.4 ECHAM

### 2.4.1 Model description

The ECHAM5 simulations have been carried out in T42 horizontal resolution ( $\sim 2.8 \times 2.8$  degrees) on 19 vertical levels with the model top at 10 hPa and a timestep of 30 min. All simulations used climatological sea surface temperature and sea-ice extent. The simulation has been integrated for 5 years after a 3 months spin-up with an output frequency of 3 h.

The version of ECHAM5 used in this study has been described in Lohmann and Hoose (2009). It includes the two-moment aerosol scheme HAM that predicts the aerosol mixing state in addition to the aerosol mass and number concentrations (Stier et al., 2005). The size-distribution is represented by a superposition of log-normal modes including the major global aerosol compounds sulfate, BC, organic carbon, sea salt and mineral dust.

### 2.4.2 Model ice cloud and related processes

The stratiform cloud scheme consists of prognostic equations for the water phases (vapour, liquid, and solid), bulk cloud micro-physics (Lohmann and Roeckner, 1996), and an empirical cloud cover scheme (Sundqvist et al., 1989). The micro-physics scheme includes phase changes between the water components and precipitation processes (autoconversion, accretion and aggregation). Moreover, evaporation of rain and melting of snow are considered, as well as sedimentation of cloud ice. It also includes prognostic equations of the number concentrations of cloud droplets and ice crystals and has been coupled to the aerosol scheme HAM (Lohmann et al., 2007). It assumes that cirrus clouds form by homogeneous freezing of supercooled solution droplets (Lohmann et al., 2008). Detrainment of cloud water and ice from convective clouds is a source for stratiform clouds. Rain and snow are treated diagnostically assuming that both raindrops and snow flakes that are not evaporated or sublimated,

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respectively, reach the surface within one time step.

## 2.5 CAM3

### 2.5.1 Model description

The Community Atmospheric Model 3 (CAM3), described by Collins et al. (2006), is the sixth generation of the community atmospheric general circulation model released by the National Center for Atmospheric Research. The atmospheric model is integrated together with the Community Land Model (Bonan et al., 2002; Oleson et al., 2004), a thermodynamic sea ice model (Briegleb et al., 2004), and either a data ocean or a slab-ocean model for equilibrium climate response studies. The set of sub-grid scale physical parameterisations used in the model is documented in Collins et al. (2006). Further information can be found at: <http://www.cesm.ucar.edu/models/atm-cam/docs/description/>.

The version of CAM3 employed here used the Eulerian dynamical core at T42 spectral truncation, which is approximately  $2.8 \times 2.8$  degrees on a Gaussian grid and a hybrid  $\eta$ -coordinate with 26 levels in the vertical. The model was run from September 2001 to January 2009 using sea surface temperatures and sea ice fractions from the data set of Hurrell et al. (2008), and the output frequency time was 3 h.

### 2.5.2 Model ice cloud and related processes

The treatment of micro-physics and cloud condensate have been substantially revised in CAM3 (Boville et al., 2005). The diagnostic cloud-water scheme used in CAM2 and Community Climate Model version 3 (CCM3) has been replaced by the single-moment prognostic cloud-water parameterisation of Rasch and Kristjansson (1998), updated by Zhang et al. (2003). CAM3 includes separate evolution equations for the liquid and ice-phase condensate. The parameterisation of deep convection is based on the work of Zhang and McFarlane (1995), but extended such that the convective cloud fraction is

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explicitly included in the model. Both deep and shallow convection parameterisations detrain cloud condensate directly into the stratiform clouds.

The settling velocities for liquid and ice-phase constituents are computed separately as functions of their respective effective radii. Small ice particles are assumed to fall like spheres according to the Stokes equation. The fall speeds of larger ice particles are calculated following Locatelli and Hobbs (1974). The fall velocities of liquid drops are treated using the Stokes equation for their entire size range. The amount of snow was, for this study, estimated from the diagnostic parameters of the rate of production of precipitation and the rate of evaporation of precipitation.

## 2.6 EC-EARTH

### 2.6.1 Model description

Project EC-EARTH aims to develop a new Earth System Model that will be used, and further developed, by several European countries. These countries are exclusively members states of the European Centre for Medium-Range Weather Forecasts (ECMWF). The resulting model consists of an atmospheric general circulation model (Integrated Forecast System, IFS), an ocean general circulation model (Nucleus for European Modelling of the Ocean, NEMO), a sea-ice model, a land model, and an atmospheric chemistry model, with the possibility of adding more sub-models. EC-EARTH was configured, for this study, with a circa  $1 \times 1$  degree horizontal resolution and 62 vertical levels (T159L62) using prescribed sea surface temperatures. The model was run for 2001–2008 with an output frequency time of 3 h.

### 2.6.2 Model ice cloud and related processes

The cloud scheme used in IFS cycle 31r1, and also in this study, is described in detail in Tiedtke (1993). Liquid and ice cloud water are treated as prognostic variables in the model. Frozen precipitation, however, is a diagnostic variable that is extracted via

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auto-conversion from ice water content and assumed to fall to the ground between time steps.

The amount of frozen precipitation at each model level was estimated by converting the fluxes of frozen precipitation to a representative mass ratio. In order to achieve this, an assumption of a bulk fall speed of  $1 \text{ ms}^{-1}$  was assumed. Both the convective and stratiform frozen precipitation was then added to the IWC to obtain a total IWC.

## 2.7 ERA-Interim

ERA-Interim is the successor to ERA-40 (Uppala et al., 2005), and is a global atmospheric reanalysis of the period 1989 to present. The IFS version Cy31r1/2 is common to both EC-Earth and ERA-Interim. EC-Earth's IFS cycle, however, contains physics packages from later IFS cycles. ERA-Interim includes assimilated measurements but the measurements considered in this study are not included. Monthly mean 6-hourly data covering 2001–2009 are considered. A motivation for including ERA-Interim data in the comparison is that it serves as a valuable reference to both the considered measurements and EC-EARTH.

## 3 Observation results

The focus of this section is to compare and examine the observations of water in the tropical upper troposphere. The upper tropospheric layer considered is located around 190 hPa (12.75 km) in altitude, with a vertical extension of  $\sim 5$  km.

This layer is chosen because the Odin-SMR retrieval accuracy of both RH<sub>i</sub> and IWC is relatively good at this layer (Ekström et al., 2007; Rydberg et al., 2009). AURA-MLS retrieved RH<sub>i</sub> are interpolated to 190 hPa, and have roughly the same vertical resolution as Odin-SMR. Thus, no further modification is made to this product. Cloud-Sat retrieved IWC profiles are averaged in the vertical dimension to match Odin-SMR vertical resolution.

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Multi year seasonal mean fields from the boreal winter and spring period are considered. This period is chosen to be studied because during this period Odin-SMR provides a more uniform geographic coverage. A problematic clustering of the observations occurs during the summer period.

Although Odin-SMR has been in operation for a longer time period than both AURA-MLS and CloudSat the Odin dataset is much smaller than the other two. Thus, a relatively broad averaging of data is considered due to the limited size of the Odin dataset. All data have been averaged in the following way: First, an averaging over  $1.5^\circ \times 1.5^\circ$  in latitude and longitude was performed for the different local time winter and spring measurements. Then a running mean averaging with a resolution of  $9^\circ \times 9^\circ$  in latitude and longitude is performed for the winter and spring measurements. The winter and spring averages are then combined.

**3.1 Relative humidity**

Odin-SMR and AURA-MLS retrieved upper tropospheric RH<sub>i</sub> have earlier been shown to compare well, with differences between regional averages of less than 10% (Ekström et al., 2008; Rydberg et al., 2009). Figure 1 shows multi-year, winter and spring, retrieved RH<sub>i</sub> fields at around 13 km in altitude from Odin-SMR and AURA-MLS from their night/morning/noon/afternoon measurements. The geographical patterns of RH<sub>i</sub> are in good agreement between the datasets. High RH<sub>i</sub> is found over regions associated with strong convection; Central Africa, South America and the maritime continent. In general, RH<sub>i</sub> decreases with increasing distance from these convectively active regions. Low RH<sub>i</sub> are found in tropical regions associated with large scale descent, as, for example, the North Pacific. Figure 1 illustrates that humidity distribution in the tropical upper troposphere is controlled by several factors, including convective systems, detrainment of water vapour and condensed water from those systems, and large scale atmospheric circulation.

Figure 1 also shows contour lines to highlight consistencies and possible differences between the datasets. Maybe the most clear difference is that band of RH<sub>i</sub> >60% along

the South Pacific convergence zone is significantly more narrow for Odin-SMR, for an unknown reason.

There are relatively small temporal variations in the RHi=60% contours compared to the RHi=80% contours. The area enclosed by the RHi=80% contour is a minimum around noon and maximises in the early evening over land and early morning over the maritime continent. This phase is in line with previous studies, e.g. Chung et al. (2007).

In Fig. 2 the datasets are compared in a more quantitative way, in order to search for any obvious systematic bias and spurious features. The figure shows retrieved RHi cumulative distributions and mean values within six climatologically varying regions as shown in Fig. 3. The distributions and mean values over the North Pacific region (lower right panel), where small diurnal variations are expected, are in good agreement. Thus any possible bias between the measurements should be within a few %RHi for dry regions.

For the wet regions, Odin-SMR shows less step distributions. This should mainly be a combined effect of that both the precision of each retrieval is poorer and the number of measurements is lower for Odin-SMR. That is say, some impact of natural variability and measurement errors remain after the spatial averaging. This corresponds to the fact that the RHi fields in Fig. 1 are less smooth for Odin-SMR. In fact, the distribution of Odin-SMR for the Maritime Continent at 06:00 shows that an average above 100% has been obtained for a part of the region. The retrieval database contains cases with a RHi above 100%, but distributed in such way that “true” averages should not show super-saturation (though individual retrievals can have  $RHi > 100\%$ ). Our interpretation is then that the distribution differences are mainly caused by remaining random components in the Odin-SMR data, and less indications on systematic deviations.

The poorer statistical basis of Odin-SMR is also the reason to why the analysis is restricted to averages over complete regions. The mean values in Fig. 2 are the actual data that will be used below. These values give a single diurnal maximum (and minimum) for all regions, which should be the expected pattern. This can only be achieved if systematic errors are small, or common, for both instruments.

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In summary, we confirm from earlier studies that regional averages of RH<sub>i</sub> from Odin-SMR and AURA-MLS are in good agreement, with a bias possibly considerably smaller than the 10% RH<sub>i</sub> previously reported. However, the good agreement shown here is only valid for this particular layer, and a lower consistency has been shown for a layer around 127 hPa (Ekström et al., 2008). We conclude that for the 190 hPa layer some of the difference is due to diurnal variations, and that it could be attempted to combine the datasets for a study of diurnal variations.

### 3.2 Ice water content

Figure 4 is similar to Fig. 1 but shows retrieved IWC from Odin-SMR and CloudSat. The overall patterns of ice mass agree well in general between the dataset, although the Odin dataset is more noisy than the CloudSat dataset. Regions with high mean IWC and RH<sub>i</sub> match quite closely as is expected. Additionally, no ice mass is found over the relatively dry regions (see Fig. 1), which is also expected because ice particles will evaporate during transport and mixing with unsaturated air. Thus, the amount of ice mass should mainly be determined by the strength of relatively local convection. Over tropical land convective regions, the concentration of ice mass appears to be higher during the day compared to nighttime. The opposite is true for convective ocean regions. These phase relationships are consistent with previous studies on occurrence frequencies of deep convective clouds (e.g., Hong et al., 2006). The contour lines shows regions with IWC > 6 mgm<sup>-3</sup>. Although Odin data are more noisy, these regions shows a fairly consistent “time evolution” pattern. Thus, the datasets are considered to be consistent, with no obvious bias apparent at this stage.

As ice mass values have a large dynamic span and are not Gaussian distributed care must be taken when analysing mean values. Fig. 5 shows retrieved IWC distributions for various regions. In Fig. 5 the distributions are for individual retrieved IWC values for Odin-SMR within the regions, whereas CloudSat data have been averaged in the horizontal dimension to match Odin-SMR resolution.

Over Africa and S. America, the distributions of CloudSat 13:30 and Odin-SMR 18:00

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show that significantly more ice mass is retrieved from those measurements than from the night and morning. The frequency of  $IWC > 100 \text{ mgm}^{-3}$  is greatest from CloudSat 13:30 measurements, whereas Odin-SMR 18:00 reports a significantly greater frequency of  $IWC > 10 \text{ mgm}^{-3}$ . This is likely due to the fact that CloudSat 13:30 observes clouds at a time close to the peak of convection and Odin-SMR 18:00 observes the clouds at a later stage in their development.

Over the tropical ocean regions the distributions show less variation than over tropical land. The tendency is that Odin-SMR 18:00 reports a relative low frequency of  $IWC > 10 \text{ mgm}^{-3}$  and low mean value. Over the Maritime continent mean IWC is higher for CloudSat than for Odin-SMR. The distributions show no large variations although they indicate that Odin-SMR observe the clouds at a later stage in their development. This is the case since a somewhat higher frequency of  $IWC < 3 \text{ mgm}^{-3}$  is reported from Odin-SMR measurements. Over the North Pacific there is basically very little ice mass.

The regional averages (text in Fig. 5) show a single diurnal maximum/minimum for four of the regions. One of the exceptions is the North Pacific region. A somewhat better sensitivity of CloudSat to thin clouds could explain the systematic difference between the two sensors for this region. This issue is of smaller importance for other regions, where the average is controlled by thick clouds. The other exception is the Maritime Continent region. This region covers both land and ocean areas, and a mix of the diurnal cycles is probably observed. This is discussed further below.

In summary, the distributions shows realistic features and are consistent to what can be expected from previous observations. As variations also can be found in mean values, and no obvious bias can be found in the distributions, we consider that no strong bias is expected to be found in the variation of the mean values. It should be pointed out that a strong correlation in a possible IWC retrieval bias is expected due to the fact that the retrievals are based on the same micro-physical assumptions. This will be taken into account in the following sections.

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### 3.3 Diurnal variations

In the previous sections, it was demonstrated that there is sufficient consistency in the different satellite products to consider studying the diurnal cycle by combining the datasets. In this section we will estimate mean values, amplitude of the diurnal variations, and phase for the regions defined in Fig. 3.

To provide estimates of these variables we make a number of assumptions. The diurnal variations of both RHi and IWC ( $x$ ) are approximated by a diurnal harmonic

$$x(t) = \bar{x} + A \cdot \cos\left(\frac{2\pi}{24}(t - \phi)\right) + \epsilon, \quad (1)$$

where  $\bar{x}$  is the daily mean,  $A$  the amplitude,  $t$  the time (in hours), and  $\phi$  the phase. The simple form assumed for the diurnal variation (Eq. 1) was chosen because the datasets provide only four separate time inputs per day. This precludes meaningfully fitting of higher order diurnal terms. We derive the quantities in a weighted least square procedure. In this way an error covariance matrix takes into account the fact that the measurements considered are correlated and have different errors. We only take systematic retrieval uncertainties into account, as the retrieval precisions are negligible for the broad averages considered.

For RHi we assume that both Odin-SMR and AURA-MLS  $1-\sigma$  retrieval systematic uncertainties are 10 %RHi. Ekström et al. (2007) derived a 30 %RHi worst case systematic error estimate for Odin-SMR, but treating the sources as independent we obtain a  $1-\sigma$  estimate of approximately 10 %RHi. The assumed 10 %RHi value is also consistent with a satellite derived RHi climatology comparison study by Ekström et al. (2008). We consider that the systematic errors for Odin-SMR and AURA-MLS are uncorrelated but that their respectively a.m. and p.m. systematic errors are strongly correlated (correlation coefficient of 0.9).

For Odin-SMR derived IWC there are three sources that dominate the systematic retrieval uncertainty. These are: (1) the assumed particle size distribution (PSD), (2) the assumed particle shapes and refractive index, and (3) cloud inhomogeneity effects,

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and estimated in Eriksson et al. (2007) to give rise to a systematic  $1\text{-}\sigma$  uncertainty of 30%, 15%, and 30%, respectively. However, the Odin-SMR data considered, were retrieved from an improved algorithm, presented in Rydberg et al. (2009), that treats cloud inhomogeneity effects more accurate. We assume that the corresponding systematic retrieval uncertainty now is 15%. This yields an Odin-SMR total  $1\text{-}\sigma$  retrieval uncertainty of 37%. The CloudSat data are retrieved using identical micro-physical assumptions as for Odin-SMR. We assume that the systematic retrieval uncertainty related to the micro-physics will be identical as for Odin-SMR. However, cloud inhomogeneities are not considered to be a large retrieval issue for CloudSat, and we assume that no systematic error is introduced due to cloud inhomogeneities. This yields an estimated  $1\text{-}\sigma$  total retrieval uncertainty for CloudSat of 33%. This value is consistent to the fact, that the official IWC product from CloudSat is reported to have a bias less than 40% (Austin et al., 2009).

We assume that the PSD dependent systematic retrieval uncertainty for Odin-SMR p.m. measurements is correlated with the PSD uncertainty for all other measurements, e.g. CloudSat a.m. measurements. A correlation coefficient of 0.9 is assumed. This level of correlation is assumed for all individual uncertainty sources (3 for Odin-SMR and 2 for CloudSat) between the a.m. and p.m. measurements for all combination of measurements. This results in Odin-SMR a.m. and p.m. error correlation coefficient of 0.9, CloudSat a.m. and p.m. error correlation coefficient of 0.9, and Odin-SMR a.m./p.m. and CloudSat a.m./p.m. error correlation coefficient of 0.83.

As the retrievals from Odin-SMR and CloudSat considered are based on the same PSD assumption, the systematic uncertainties are correlated. As a result, the diurnal mean values can not be determined very accurately. On the other hand, the correlations allow for accurate estimates of relative amplitudes ( $A/\bar{x}$ ) and phases.

Results obtained for RHi are presented in Table 1. The amplitude is most significant over Africa and S. America ( $\sim 6$  and  $8\%$ RHi), the maximum occurring in the early evening. The amplitude is about twice as large over tropical land than over tropical ocean region where the amplitude is below  $\sim 3\%$ RHi, but with uncertainties almost as

great. The maximum over ocean regions is estimated to be in the early morning.

The observations are in fair agreement with results from Chung et al. (2007), who reports a UTH peak around 02:00–03:00 over tropical land (Africa), and a broad peak during the night is found over ocean (tropical Atlantic). Additionally, the reported amplitude over land ( $\sim 2\%$ ) is about twice as large as the amplitude over oceans ( $\sim 1\%$ ). The relatively large amplitude reported from this study compared to previously published results, can, in part, be explained by the fact that the regions considered here are centred over convectively active areas and a somewhat higher located altitude layer is here considered. The vertical layer considered is centred around 190 hPa, whereas UTH normally refers to 500–200 hPa.

Results obtained for IWC are presented in Table 2. Over Africa and South America the results are similar with relatively high mean values, amplitudes of  $\sim 50\%$  of the mean value and a maximum in the afternoon. The timing of the maximum is in line with Hong et al. (2006), who used data from the PR (Precipitation Radar) and VIRS (Visible and Infrared Scanner) onboard the Tropical Rainfall Measuring Mission. They noted that, over tropical land, the occurrence frequency of deep convective clouds peaks around 14:00–16:00 h local time according to the PR and 16:00–18:00 h local time according to VIRS ( $T_{11} < 210$  K), and the occurrence frequency of high cold clouds ( $210$  K  $< T_{11} < 235$  K) peaks around 16:00–18:00 h local time (VIRS).

Over tropical Indian and Pacific ocean mean values are somewhat lower than over the land regions, and the maximum is estimated to be in the early morning. Hong et al. (2006) found a maximum in deep convective clouds around 04:00–06:00 (PR) and 05:00–07:00 (VIRS). Additionally they found that the peak of high cold clouds lags the peak of deep convective clouds by 7–9 h. However, as these clouds are expected to be remnants of deep convective clouds one would expect that some ice mass has evaporated or fallen out since the injection of the ice mass, so that the ice mass is lower around noon. This is also observed.

Over the Maritime continent Hong et al. (2006) found that the diurnal cycle of clouds can be understood as a combination of that over land and ocean. This means that

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one would expect to see relative high IWC throughout the day and a double maxima in IWC. However, this variation can not be fully resolved by measurements from only four times during the day. We observe a high mean value and low amplitude, which to some extent agree with results from Hong et al. (2006).

5 In summary, the IWC observations show that maxima in IWC are found close in time to the peak in the occurrence frequency of deep convective clouds. This indicates that the amount of ice mass in the upper troposphere is primarily determined by the strength of convection.

## 4 Model-data comparisons

10 In this section we compare observed diurnal variations of RHi and IWC with corresponding results from climate models and ERA-Interim. We consider the mean, amplitude, and phase inside the regions defined in Fig. 3. The model data are averaged according to how the measurements are averaged (Sect. 3). Mean values are strictly the mean value of the parameters for the different output times. Amplitude is half the  
15 difference between maximum and minimum value. The phase corresponds to the local time of the maximum value.

### 4.1 Relative humidity diurnal variations

Figure 6 shows measured and modelled diurnal variations of RHi. Mean values from observations are in excellent agreement with ERA-Interim values which provides further confidence in the measurements. It is stressed that ERA does not assimilate the  
20 observations considered.

ECHAM is in general wetter, while CAM3 drier (except N. Pacific) than the measurements. The dynamical range in RHi of CAM3 and ECHAM data is significantly lower than the measured. Thus, these models seem to underestimate the tropical geographical RHi variability. EC-EARTH data fit within the measured  $2\text{-}\sigma$  uncertainty, and are  
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close to ERA values. This indicates that the IFS does not have to rely on assimilated measurements to produce realistic RHi mean values. This in its turn gives strong support to the relatively recently implemented parameterisation for ice supersaturation in IFS by Tompkins et al. (2007). EC-EARTH simulations were performed on a ~3 times finer horizontal resolution than for ECHAM and CAM3, which might be one reason for why EC-EARTH better capture the geographical RHi variability.

All models show a greater amplitude over land than over ocean regions, which is consistent with the measurements. However, the observed amplitudes ( $\pm 1\sigma$ ) over land are in general much greater than the modelled. This indicates that the strength of convection over land is too weak in the models.

Estimated and ERA phases are in reasonable agreement, beside for the North Pacific region. The observed and modelled phases are consistent over the ocean and maritime continent regions, beside CAM3 for Tropical Indian. EC-EARTH follows the measured phases closely except over the pure land regions, where EC-Earth deviates from all other data sources. This indicates that the IFS are more dependent on measurements over the tropical land region, than over the ocean regions.

The CAM3 results shown here are consistent with the results of Rasch et al. (2006) who studied the tropical transient activity of the hydrological cycle simulated by CAM3 by comparing model output with Tropical Rainfall Measuring Mission precipitation estimates and Global Cloud Imagery cloud brightness temperatures (Salby et al., 1991). They concluded that the transient aspects of convection in CAM3 were too weak and that the ratio of stratiform to convective rainfall was too low (by a factor of between 4 and 5). These conclusions are consistent with an earlier study using Community Climate System Model version 2 by Dai and Trenberth (2004) who hypothesised that moist convection in the model occurred too frequently and lasted too long, removing water vapour prematurely and too efficiently.

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## 4.2 Ice water content diurnal variations

Figure 7 shows measured and modelled diurnal variations of IWC. A direct comparison between observations and model output is complicated by the fact that the measured and modelled IWC represents different quantities (see Sect. 2). However, in Fig. 7 model results for both the prognostic IWC (in-cloud ice mass) and total IWC (prognostic + diagnostic IWC or precipitating ice mass) are included. However, this is not the case for the ERA-interim data, which only contains prognostic IWC, and no data on precipitating ice is available. The North Pacific region is excluded from the discussion below as it basically contains no ice mass.

The in-cloud ice constitutes 60–90% of the total ice mass in this altitude region, according to the models. A much higher fraction of the cloud ice is found as precipitating at lower altitudes (not shown). If any difference exists, it should be expected that the relative amplitude is higher for total than in-cloud ice. The models show also this feature, with the exception of CAM over South America. However, the models give in general limited differences for the relative amplitudes and the phases between ice-cloud and total ice.

Although, most models mean IWC values are within the observed  $2\text{-}\sigma$  uncertainty, they are outside the  $1\text{-}\sigma$  uncertainty (biased low), except EC-EARTH over the tropical ocean regions. The low bias of the ERA-Interim data is not surprising given that this data set represents only smaller ice particles as described above. Even though the models total IWC values are in general lower than the measured values the relative geographical variation are fairly consistent with the measured. For example, CAM3 and ECHAM values are approximately a factor of 2–3 lower than the best measurement estimate for all regions considered.

The derived relative amplitudes are in fair agreement with ERA except over the Tropical Indian region, where the estimated amplitude is greater. Over ocean regions the models tend to underestimate the amplitude, while EC-EARTH and CAM3 overestimate the amplitude over land (in relative terms). Over the maritime continent, where

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there diurnal variation is relatively weak, the models and measurements agree. EC-EARTH and ERA produce fairly consistent amplitudes except over tropical land.

The modelled phases of CAM3 show little difference between land and ocean regions and do not match the measurements except over the Maritime Continent. Assuming the diurnal cycle of IWC is strongly linked to convective activity, these results tend to imply that the timing of tropical convection in CAM3 is poorly simulated although the measurement data here are insufficient to conclusively confirm this. Rasch et al. (2006) showed that CAM3 tended to produce maxima in tropical precipitation and liquid water path that were a few hours earlier than seen in observations over both oceans and land.

ECHAM and EC-Earth phases show a better agreement with the measurements, but some deviations can be noted. ECHAM poorest region for this variable is Tropical Indian. EC-Earth gives a phase over Africa and South America that is some hours too early. This shortcoming is probably the main cause to the also too early phase for RHi for these regions in EC-Earth. The measurements give a RHi peak approximately 6 h after IWC for the two land regions. This phase difference is lower in EC-Earth, while it is higher in ECHAM with 12 and 7 h for Africa and South America, respectively. The CAM RHi/IWC phase differences for Africa and South America compare reasonably well with the observations but the timing of both the IWC and RHi peaks occur later than observed. Over the two pure ocean regions with substantial IWC (Tropical Indian and Pacific), the results (excluding CAM) indicate that RHi and IWC peak at roughly the same time (around 05:00).

The relative timing of the RHi and IWC peaks is an indicator of the processes important in moistening the tropical upper troposphere. From the results shown here, there appears to be a difference in the characteristics of this moistening process over tropical land masses compared to tropical ocean regions which the models have difficulty capturing.

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## 5 Conclusions

There is a limited amount of information about the water budget and its variations in the upper troposphere. Previous measurement studies of clouds and humidity in this region have primarily been based on infrared sensors. Such sensors are not ideal for studying the amount of ice in thick clouds. In this study a combination of observations from microwave and sub-mm instruments (CloudSat, Aura-MLS, and Odin-SMR) is used to study the diurnal cycle of water in the tropical upper troposphere. All three instruments are placed in polar sun-synchronous orbits with tropical local observation times at 01:40 a.m. and p.m. for CloudSat and AURA-MLS and 06:00 a.m. and p.m. for Odin-SMR. The atmospheric layer considered is centred around 190 hPa and parameters examined are relative humidity w.r.t. ice (RHi) and ice water content (IWC).

First and foremost, it is found that observations of average RHi from Odin-SMR and AURA-MLS are in good agreement with differences of only a few %RHi. Furthermore, IWC retrievals, based on identical micro-physical assumptions, from Odin-SMR and CloudSat are also found to be in good agreement. Differences between the datasets are believed to be mainly an effect of diurnal variations.

Estimates of relative IWC diurnal variations with high accuracy are obtained. Over tropical land regions an afternoon maxima is observed, and over ocean regions an early morning maxima is observed. Over the maritime continent, a relatively high mean IWC value is observed throughout the day. The observed IWC phases coincide with the peak of the occurrence frequency of deep convective clouds reported by Hong et al. (2006).

Most significant diurnal RHi variations are found over tropical land regions, with the maximum occurring around midnight, approximately 6 h after the IWC maximum. Over tropical oceanic regions RHi variations are less significant, but the observations indicate a maximum in the early morning.

It should be clear that a more detailed view of the diurnal cycles has been obtained by combining MLS/CloudSata with Odin-SMR. The information gain has not

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been determined in any quantitative way, but it is noted that a single sun-synchronous satellite samples the diurnal cycle at the Nyquist limit – if the diurnal variations can be described completely by a single harmonics as in Eq. (1). The maximum (and only) frequency is then  $1/24 \text{ h}^{-1}$  and the sampling frequency is  $1/12 \text{ h}^{-1}$ . The measurements will give a lower bound on the diurnal amplitude, but it can be as low as zero. In this hypothetical case, the diurnal cycle would be determined fully by adding a second satellite, as long as it is in another orbit and all the observations are error-free. The diurnal cycles of water have more complicated structures, thus containing higher order harmonics (Jin et al., 2009), and even two satellites are in principle not sufficient. However, a more important consideration is that differences in systematic errors must be considerably smaller than the diurnal amplitude before combining satellite datasets for any practical gain.

Observed diurnal variations were compared to output from three climate models (EC-EARTH, ECHAM, and CAM3) and ERA-Interim. Observed RHi variations were found to be in excellent agreement with ERA data, but all models were found for some points to deviate from the observations. A straightforward measurement-model IWC comparison was not possible as the measured and modelled cloud ice mass represent different quantities. The amount of “snow” had to be estimated from diagnostic parameters of the models. Model output was in some instances found to deviate from the observed  $2\text{-}\sigma$  uncertainty. For example, EC-EARTH was found to be in a fair agreement with the measurements over ocean regions, but with a lower consistency over land regions. Furthermore, the modelled phases of CAM3 showed little difference between land and ocean regions and did not, for most cases, match the measurements. Although, most modelled mean IWC values are within the observed  $2\text{-}\sigma$  uncertainty, modelled IWC is likely to be biased low (outside  $1\text{-}\sigma$ ).

Significant differences in tropical upper tropospheric water variables between observations and models have been presented and discussed. This analysis points to shortcomings in the models considered here but the measurement data are insufficient to evaluate all the relevant process controlling RHi and IWC in the tropical upper

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5 troposphere. Therefore it is outside the scope of this work to investigate the reasons for disagreement between the models and the measurements. A full evaluation of the models focusing on processes including, amongst other things, the strength, depth and timing of tropical convection, the accuracy of vertical transport and the interaction between these processes and the large scale dynamics is required to understand the reasons for the model discrepancies. This is left for further studies.

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**Table 1.** RHi diurnal variations estimate together with uncertainties ( $1-\sigma$ ).

Region	Mean [%RHi]	Amplitude [%RHi]	Phase [h]
Africa	74.3±6.9	6.1±2.5	23:00±3.0
T. Indian	60.3±6.9	1.4±1.7	04:00±3.0
M. continent.	81.0±6.9	3.2±1.9	04.30±3.5
N. Pacific	31.7±6.9	2.1±1.9	21:00±5.0
T. Pacific	68.5±6.9	3.0±1.8	06:00±4.0
S. America	80.1±6.9	7.9±2.8	22:00±3.0

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**Table 2.** IWC diurnal variations estimates together with uncertainties ( $1-\sigma$ ).

Region	Mean [ $\text{mgm}^{-3}$ ]	Relative amplitude [-]	Phase [h]
Africa	$6.4 \pm 2.4$	$0.51 \pm 0.06$	$18:00 \pm 1.5$
T. Indian	$4.6 \pm 1.5$	$0.52 \pm 0.06$	$05:30 \pm 1.5$
M. continent	$7.1 \pm 2.5$	$0.11 \pm 0.09$	$01:00 \pm 4.0$
N. Pacific	$0.4 \pm 0.2$	$0.41 \pm 0.10$	$08:00 \pm 2.0$
T. Pacific	$6.9 \pm 2.3$	$0.28 \pm 0.06$	$05:00 \pm 2.0$
S. America	$6.9 \pm 2.3$	$0.38 \pm 0.07$	$16:00 \pm 2.0$

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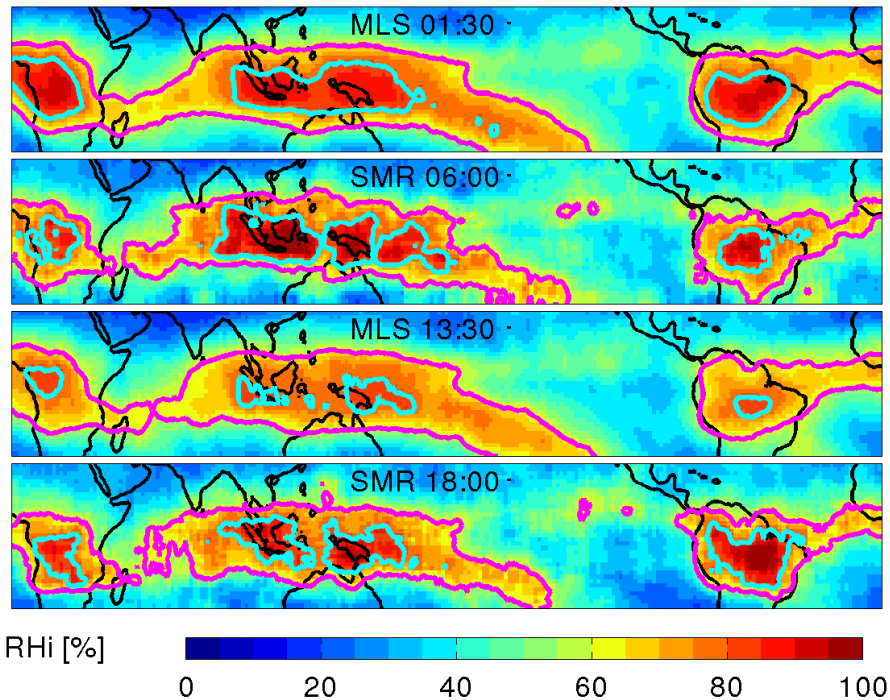
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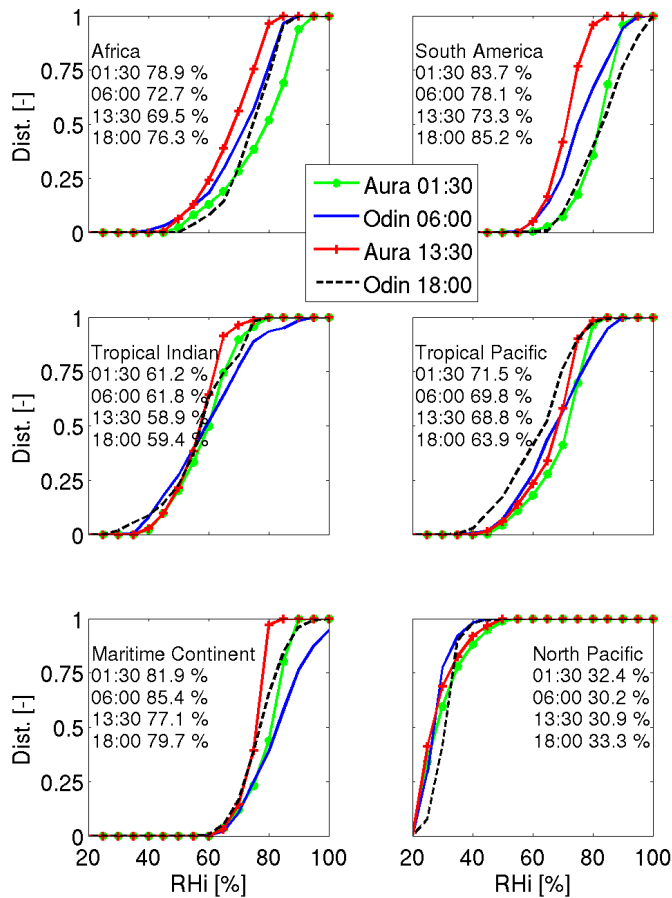
**Fig. 1.** Multi-year boreal winter and spring RHi fields around 190 hPa derived from Odin-SMR and AURA-MLS. The cyan and blue contour lines mark regions with  $RHi > 60\%$  and  $RHi > 80\%$ , respectively. Data averaging is described in the text.

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**Fig. 2.** RHi cumulative distributions of the data shown in Fig. 1 for various regions as defined in Fig. 3. The text in the panels gives the average for each distribution.

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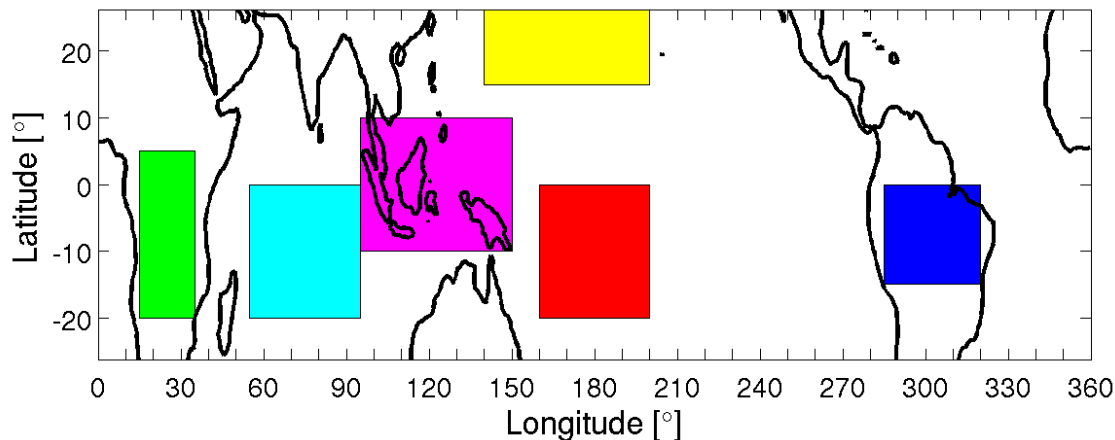
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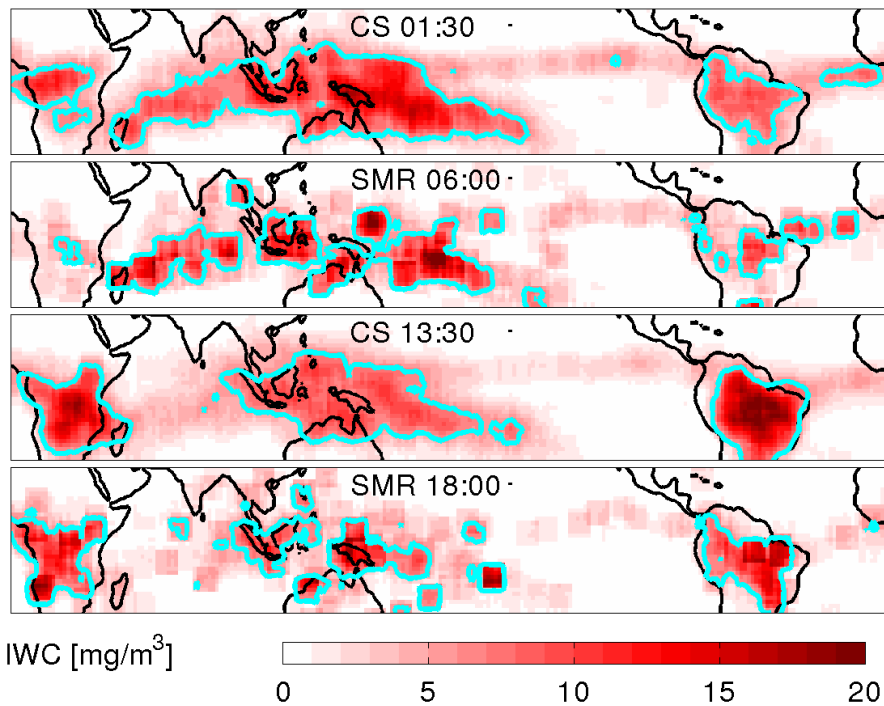
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**Fig. 3.** Definition of selected regions (green = Africa, cyan = Tropical Indian, magenta = Maritime Continent, yellow = North Pacific, red = Tropical Pacific, and blue = South America).

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**Fig. 4.** Multi-year boreal winter and spring IWC fields around 190 hPa derived from Odin-SMR and CloudSat. The cyan contour line marks regions with  $IWC > 6 \text{ mg m}^{-3}$ . Data averaging is described in the text.

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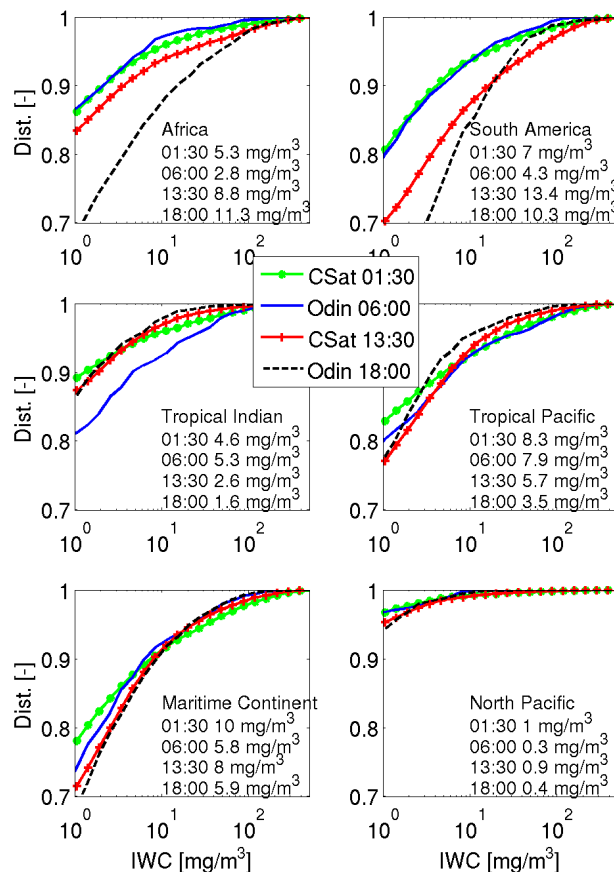
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**Fig. 5.** IWC distributions of the data shown in Fig. 1 for various regions as defined in Fig. 3. The text in the panels gives the average for each distribution.

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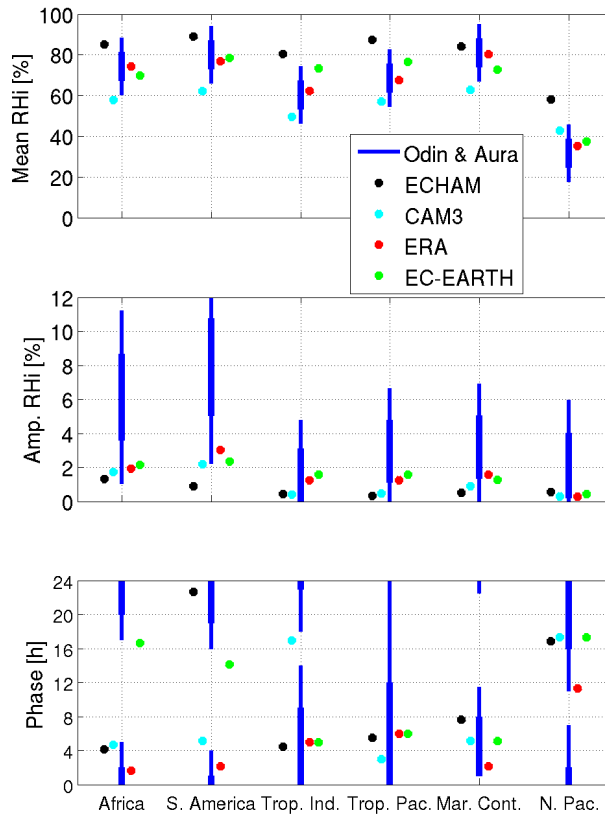
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**Fig. 6.** Multi-year boreal winter and spring observed and simulated RHi diurnal variations around 190 hPa for the regions defined in Fig. 3. The thick part of the blue lines corresponds to  $\pm 1\text{-}\sigma$  and the thin part to  $\pm 2\text{-}\sigma$  of the satellite estimates.

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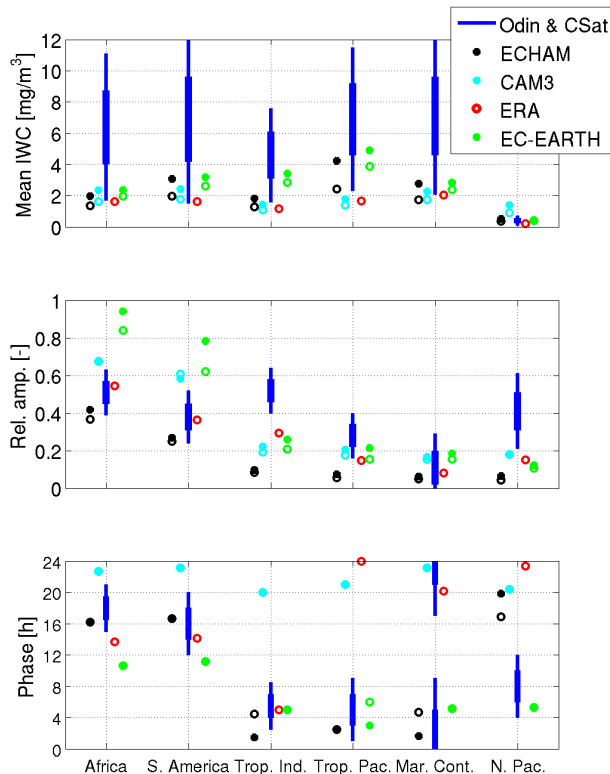
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**Fig. 7.** Multi-year boreal winter and spring observed and simulated IWC diurnal variations around 190 hPa for the regions defined in Fig. 3. The thick part of the blue lines corresponds to  $\pm 1\text{-}\sigma$  and the thin part to  $\pm 2\text{-}\sigma$  of the satellite estimates. The filled dots and circles represent model total cloud ice mass and in-cloud ice mass, respectively (see text for clarity).