The 2015 Indian summer monsoon onset - phenomena, forecasting and research flight planning

The 2015 Indian Summer Monsoon Onset - Phenomena, forecasting and research flight planning

For submission to Weather

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Forecasting the 2015 Indian Monsoon Onset

Abstract

From May to July 2016, as part of the INCOMPASS project, the Facility for Airborne Atmospheric Measurements (FAAM, jointly funded by the Met Office and NERC) BAe-146 research aircraft travelled to India to record key aspects of the Indian summer monsoon onset and evolution (Turner et al., 2016). As part of the planning for the campaign, partners in the UK and India took part in a "dry-run" forecasting exercise during 2015, to assess the reliability of the forecast products and develop a set of flight plans, in advance of the real campaign, and to get a real-time feel for the monsoon onset.

5-day forecasts from the Met Office and the Indian National Centre for Medium Range Weather Forecasting (NCMRWF) showed good skill in terms of predicting the advance of rainfall in regions key for the campaign in north and south India, and captured transitions from active (wet) monsoon conditions to break (dry) periods and back again.

Key phenomena seen during the dry-run exercise include (1) a "western disturbance", which had a major effect on the extreme pre-monsoon heatwave conditions over India, (2) dry intrusions, which are thought to be important in the progression of the monsoon onset against the synoptic flow, and (3) cyclones Ashobaa and Komen.

Keywords: Indian Monsoon, BAE-146 Research Aircraft, INCOMPASS, Onset, Dry Intrusion, NCMRWF, Met Office

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1. Introduction

The Indian summer monsoon is one of the most dramatic seasonal variations in climate, characterised by the reversal of prevailing winds between winter and summer that brings moisture from across the Indian Ocean during the monsoon. The monsoon lasts from June to September and supplies India with around 80% of its annual rainfall. With more than a billion people to feed, the monsoon is vital to Indian society. The most important event in the meteorological calendar for India is the monsoon onset. This first occurs around 1 June, in Kerala on the southwest coast (figure 1), and then progresses north and northwestwards, arriving in Delhi before July and reaching the Pakistan border around 15th July. At each location, the arrival of the monsoon rains brings cooler conditions to replace the pre-monsoon heat, and is vital to farmers in regions where irrigation is not available, as well as to the coal and steel industries. Delayed onset can cause drought and hardship; violent rains around the time of onset can cause flooding and landslides, and every year thousands are killed by lightning, most of whom are farmers working in fields.

To first order, the mechanism behind the formation of the monsoon is straightforward, involving the reversal of the tropospheric temperature difference over land and ocean (warmer over land during summer), which generates a sea breeze into the subcontinent (land breeze in winter). This is enhanced by further warming of the troposphere from intense sensible heating over the Tibetan Plateau (Li and Yanai, 1996), by the local role of the Himalayas in blocking cool, stable air from reaching South Asia (Boos and Kuang, 2010) and by the effect of the East African highlands in shaping the low-level Somali jet (e.g. Slingo et al., 2005), which is the main transporter of moisture into the subcontinent during the summer. However, the physics behind the monsoon onset are more complex. While the first rains over southwest India coincide quite neatly with the reversal of the temperature gradient (Xavier et al., 2007), the first rains progress in a northwestward direction, perpendicular to or even opposing the mean flow (Parker et al., 2016). Briefly, onset over the whole of the Indian subcontinent is retarded by dry air intruding from the northwest above the surface layer, while initial storms in the south and over newly wet soils pre-moisten the free troposphere for further development of deep convection later.

Being able to model and forecast the monsoon is therefore an important goal of meteorological research, but despite the importance to society, forecasts of the monsoon and its onset suffer from errors on a variety of time scales, from long-term mean simulation (generally as dry biases; Sperber et al., 2013), through seasonal forecasts (e.g. Johnson et al., 2016) to Numerical Weather Prediction (NWP) forecasts where the biases develop within the first day or so (Martin et al., 2010; Mitra et al., 2011). The fact that such biases develop so quickly suggests there are errors in the way the models represent physical processes parametrization schemes (i.e. through parametrisation schemes), and in how we represent the interaction of the convective heating and large-scale circulation, and their evolution across various contrasts in the boundary layer and surface. Some of these contrasts arise owing to fixed features of the surface (land-ocean boundaries, orography, or between irrigated and non-irrigated agriculture), while others are transient features (patches of dry soil becoming wet as the monsoon advances, or changes in vegetation with the seasonal cycle).

The need to understand better the evolution of the monsoon and to quantify fluxes from the surface and boundary layer as they interact with convection and the large-scale circulation motivated the Interaction of Convective Organisation and Monsoon Precipitation, Atmosphere, Surface and Sea (INCOMPASS) project 2015-2018, a joint venture between India's Ministry of Earth Science (MoES) and the Natural Environment Research Council (NERC) in the UK. (as part of a wider South Asian Monsoon programme (http://www.nerc.ac.uk/research/funded/programmes/monsoon/). The INCOMPASS field campaign of May-July 2016 consists of an intensive period of surface and upper air measurement, comprising radiosondes, flux towers and various other instruments, together with an aircraft campaign.

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During aircraft campaigns, the day-to-day planning consists of checking NWP forecasts against most recent observations, making judgements of those forecasts against known biases, and filing appropriate flight plans in order to sample the appropriate science and pay heed to weather-related flight safety. In preparation for the 2016 Intensive Observing Period of INCOMPASS, we held a "dry-run" flight planning exercise during the onset of the 2015 monsoon, from 21 May onwards. Although no flights were actually taking place, we held daily morning briefings and used operational forecasts from the Met Office (UK) and NCMRWF (India) to track developments in the monsoon onset and other synoptic features of interest, in comparison with analyses and observations. After each briefing, we made a decision on what potential flights could be performed, with an eye on developments three or four days ahead.

This paper looks at the performance of the forecast products used for predicting the progression of the monsoon onset, and discusses some of the chief synoptic features of interest during the 2015 Indian monsoon onset, as well as briefly outlining some of the aircraft flight plans that were developed during the exercise. We conclude that such a dry-run activity is a useful addition to preparations for an aircraft observation campaign.

Forecast Models

The Met Office forecasts were provided from the operational global NWP model running the Met Office Unified Model (MetUM) GA6.1 configuration, which has a resolution of approximately 17 km in mid-latitudes and 26 km at the equator, and reaches 80km with 70 vertical levels. The standard meteorological fields are initialised using a Hybrid Ensemble 4D-Var data assimilation (DA) system described in Clayton et al. (2012) and Rawlins et al. (2007).

The NCMRWF version of the MetUM (NCUM) is the same configuration as the operational MetUM global NWP model. During the 2015 monsoon period NCUM was initialised from Met Office analyses at 00 UTC.

GloSea5 is an ensemble prediction system run operationally at the Met Office. It uses the high resolution version of the HadGEM3 atmosphere-ocean coupled climate model, which has a horizontal grid spacing of ~50 km grid spacing in the mid-latitudes

2. Monsoon 2015 Evolution

2.1 Pre-monsoon conditions and outlook

Each May India experiences severe heat wave conditions before the onset of the monsoon and its cooling rains, particularly in the northern plains region. During May 2015, heat wave conditions prevailed over northern and central India, with temperatures rising above 45°C in places and resulting in the loss of more than 2300 lives (Guha-Sapir and Below, 2016). This particularly extreme heat wave was related to unusually persistent northwesterly winds from upstream desert areas. While a series of western disturbances (a type of extratropical storm) brought some relief to northwestern parts during late May, pre-monsoon showers were largely absent. While such extreme conditions were not foreseen, long-range forecasts issued in March from the Met Office GloSea5 model did show high probability of above-normal temperatures during April-June.

In April, the IMD issued a forecast of "below-normal" rainfall for the monsoon season as a whole (around 10% below the long-term average), in part due to the influence of developing El Niño conditions, which tend to decrease rainfall over India. Onset, however, was predicted to occur as normal over Kerala (1st June). The updated "second-stage" seasonal forecast issued by IMD on 2nd

June further reinforced the below-normal projection since negative Indian Ocean Dipole conditions relaxed to neutral. Forecasts from other centres around the world were mixed, with some (including GloSea5) also tending to favour slightly below-normal conditions and others (including ECMWF) preferring slightly above-normal seasonal rainfall. All-India rainfall for the 2015 monsoon turned out to be 86% of the long-term average, and the IMD declared onset in Kerala on the 5th June.

2.2 Western Disturbance

Western Disturbances (WD) are an important feature of the weather in the northern Indian subcontinent, being seen, on average, over Pakistan and India seven to eight times a month during winter (Pant and Rupa Kumar, 1997) and producing the majority of the region's rainfall during that season. However, WDs are becoming increasingly common in spring and summer, and can cause serious flooding in the Himalayan foothills (Dimri et al., 2015). They are eastward-moving extra-tropical cyclones, which originate as low pressure systems over the Caspian or Mediterranean Seas. Weak, secondary, cyclonic circulations are often induced over Pakistan and Rajasthan in northeast India.

On 29th May, a WD over Jammu and Kashmir (a northern state, mostly in the Himalayas), and an associated induced cyclonic circulation over central Pakistan and Rajasthan (figure 2) brought rainfall to central and west Pakistan, reducing daytime temperatures by 5 to 6˚C in the region. As a result, the hot (45-50˚C) dry northwesterly afternoon winds, which normally blow over the western Indo-Gangetic Plains from the deserts of Pakistan and northeast India (locally called 'The Loo'), abated and brought an end to the heatwave.

In terms of flight planning, a Western Disturbance in itself is worth sampling. How does the boundary layer change, and how does it lead to rainfall? How does it interact with the heatwave? Being the first rainfall event over much of NW India for some time, this would be a good time to measure changes in land-atmosphere coupling due to moistening of the soil. Figure 3 shows the early afternoon land surface temperature anomaly (LST) on 29th May, which could be used as a proxy for soil moisture. The footprint of cool, wet soil is very clear, with strong negative anomalies relative to a long-term climatology.

Capturing the seasonal change in atmospheric structure as the monsoon onset progresses would require a number of flights along the same westward transect in northern India towards New Delhi (figure 1), and would involve a high-level flight (>20000 feet) known as a *dropsonde run*, launching dropsondes every 15 minutes. A dropsonde, like a radiosonde, measures a vertical profile of standard atmospheric parameters, but is dropped from an aircraft and falls to the ground under parachute, rather than being lifted from the ground by a balloon. This would be followed by a long, low-level run back over the same route in the boundary layer (normally 500ft above ground level), to measure statistics of the coupling to the land surface. A similar flight could be extended to include a region of recently-wet soil. It is possible that this flight would have been performed prior to the WD, to capture the pre-onset structure, and flying it again, soon after the first rain on dry soil, would provide some useful statistics on the changes in the land-atmosphere coupling due to rainfall, and useful information about the heatwave conditions and the WD and its effects.

2.3 Cyclone Ashobaa

The start of the 2015 monsoon season saw a particularly strong monsoon onset vortex (a cyclonic system developing in the horizontal wind shear as the westerly monsoon jet moves northwards over the Indian Ocean; see Krishnamurti et al., 1981 for a general description) develop over the south Arabian Sea. During the second week of June, this onset vortex intensified and moved north-westward towards Oman, officially being designated tropical cyclone "Ashobaa" on 6th June (figure

4(a-c)). It continued to intensify and travel with a more westward bearing until 10th June when interaction with an area of low ocean thermal energy and strong vertical wind shear forced it to weaken into a deep depression. Later, as it approached Oman, interaction with the land surface and a dry-air intrusion from the west caused it to weaken into a depression in the morning of 12th June and into a well-marked low pressure area over northwest Arabian Sea and adjoining Oman coast by that evening.

The Met Office and NCUM analyses picked up the formation of cyclone "Ashobaa" on Thursday 4th June to the west of the Indian peninsula. The subsequent passage of the cyclone north/north westwards across the Arabian Sea, and associated northward progression of monsoon onset from Kerala to Goa was forecast well in the models (figure 4(a-c)), with the position and intensity of the cyclone matching the analyses at up to 2 days lead-time.

The analysis of wind forecasts showed that forecasts initialised on 4th-6th June showed a track towards Yemen while those initialised on 7th-8th June showed an initial movement towards Yemen but slowed "Ashobaa" too soon and allowed it to be turned north and north-east towards India/Pakistan. This movement was related to interaction with a trough of low pressure over Pakistan. This also occurred in the 12UTC 7th June and 00UTC and 12UTC 8th June forecasts, and meant that at longer lead-times the models failed to capture the formation of a ridge over the Indian peninsula that prevented further northward development of the monsoon. By 00UTC 9th June the MetUM held Ashobaa sufficiently far south to prevent interaction with this trough to the north and correctly forecast a bend towards the west accompanied by deceleration and weakening. Subsequent forecasts showed the westward and subsequent slight southward movement with the dissipation of the cyclone.

Figure 5 shows data from an overpass of the CloudSat satellite at 0900UTC on 8th June, travelling south-southeastward almost directly over the vortex centre. This overpass reveals a number of interesting features: the gap in convective cloud at around 20˚N, the asymmetrical shape of the anvil as it approaches land, and a number of small convective plumes to the south. A proposed observational flight from Mumbai to Muscat and back could take soundings through this (albeit across an almost perpendicular plane), and could, for example, probe the gap at 20 ˚N to determine whether this was simply a lack of triggered convection or a developing eye. Equally, a carefully altered return flight could pass diagonally southeastward through the storm in order to quantify how the different environment in the north is forcing the cyclone to dissipate so sharply.

2.4 Dry Intrusions

Midlevel dry intrusions provide an important control on the occurrence of convective storm clouds in many parts of the tropics. In the early 1990s, the TOGA-COARE experiment over the West Pacific observed several occasions on which the arrival of an intrusion of dry air in the lower part of the troposphere acted to suppress cumulonimbus clouds for many days (Parsons et al., 2000). In these dry periods, the atmospheric profile is gradually moistened by the action of shallower convective clouds: cumulus and cumulus congestus cloud humidifying the lower troposphere, until the dry intrusion is effectively eradicated, and deep cumulonimbus convection can occur. The same effects are seen in other areas: for instance over West Africa, forecasters are using measures of mid-tropospheric humidity to delineate the leading edge of dry intrusions from the Sahara desert. The dry intrusions have a secondary role in influencing the intensity and organisation of cumulonimbus clouds when they do appear, because the presence of mid-level dry air enhances the intensity of downdraughts within storms. The downdraughts are driven by evaporation of falling rain, and this evaporation is much stronger when the air into which rain is falling is dry, in which case very severe winds can occur at the ground (e.g. Provod et al. 2016). Intense downdraughts organise the storms, making them much more intense and long-lived, and possibly causing much higher rainfall totals at the surface (Markowski and Richardson, 2010). Over the years, Ramanathan and Banerjee (1931), Sawyer (1947) and Houze et al. (2007) have shown how storms in the Indian monsoon are more well-organised and more violent when they are influenced by mid-level intrusions of dry air from the northwest. Therefore, in forecasting for India, it will be important to map out the leading edge of dry intrusions, to help show likely areas in which deep convection may be suppressed and to indicate regions in which organised, and therefore intense and sustained, cumulonimbus storms may be found.

In the INCOMPASS dry run, we examined analyses and forecasts of wet-bulb temperature (T_w), RH and equivalent potential temperature (θ_e) at 700hPa and 500hPa to delineate the intrusions of mid-level dry air. A case is shown in figure 6. Dry air at 0600 UTC (1130 local), which can be seen as streams of low relative humidity air coming into northwest India from the Arabian Sea in the west of the domain, was followed by an outbreak of moist convection at its leading edge at 1200 UTC (1730 local).

Research flights targeting a dry intrusion event would aim to characterise the thermodynamic profiles with dropsonde runs, particularly focusing on the edges of the dry intrusion in the morning, where deep convection may be expected to occur later in the day. Research flights on subsequent days, as well as analysis of the ground-based data, would be used to evaluate the processes overcoming the dry intrusion, with a return to more humid conditions.

2.5 Monsoon onset and transitions between active and break monsoon periods

Figure 7 shows the northward progression of rainfall over the Indian peninsula during June and July 2015. This shows good skill in the timing of the northward progression out to day 5, though there is a positive bias in magnitude during the active phase around 20th June.

NCUM Forecasts on 23rd June out to 4 days (not shown) suggested the development of another upper-level western disturbance and a southward shift of the Somali jet, associated with dry conditions over the peninsula. Indeed, in the days that followed, a predominance of dry northwesterly mid-level flow suppressed rainfall over the peninsula. The monsoon trough shifted north along the Himalayan foothills (accompanied by northward movement of maximum rainfall in figure 7) and monsoon low pressure systems forming in the Bay of Bengal moved northwestwards along this. These are typical of monsoon break conditions, and they persisted until around 22nd July. There was a brief recovery on the 10th/11th July associated with a northward shift of the Somali jet core to around 10°N in the Arabian Sea, but the predominance of dry northwesterly flow at mid-levels continued to suppress rainfall over the peninsula. Figure 7 indicates that the NCUM captured these transitions reasonably well in forecasts out to day 5, suggesting it could be a reliable tool in real-world flight planning.

Forecasts on 22nd July out to 3 or 4 days ahead suggested a return to active monsoon conditions with a monsoon trough becoming well established and allowing monsoon lows to track across northern India. Once again, there was good correspondence between the forecast and analyses for this transition, even at 4 days lead time.

2.6 Cyclone Komen

During July, a depression formed over the Ganges river delta and subsequently developed into cyclonic storm "Komen" by 30th July (figure 4d). This was the first cyclone-strength storm formed in the Bay of Bengal during the monsoon season for the past 25 years. Its track was also unique before and after it made landfall over Bangladesh: The depression was only at storm strength until 2nd August, but caused significant damage and flooding to parts of Myanmar, Bangladesh and West

Bengal.

Analysis of wind forecasts show that the Met Office model predicted the cyclonic storm development with the initial conditions of 27th July onwards, but the path was not captured by the Met Office and ECMWF models.

3. Assessment of forecast skill

3.1 Short-range

Figure 8 shows the spatial distribution of mean rainfall from IMD-NCMRWF observations and NCUM's day 1, 3 and 5 rainfall forecast for the monsoon season of 2015. The model forecast is in good agreement with the observed rain over the west coast, eastern parts and central India while rainfall is slightly overestimated over northeast India. Rainfall in the Indo-Gangetic plains is also well captured in all the forecasts. Analysis of the spatial distribution of maximum rainfall at each grid during the season showed that the highest rainfall over west coast, central India, Orissa and other eastern parts of India were fairly well-captured by the model until the day 5 forecast.

Examination of the Extreme Dependency Score (EDS) family of skill scores from Ferro and Stephenson (2011) and Jolliffe and Stephenson (2011) (which measure the association between the observed and forecast rare events) shows that the model has lower skill for higher rainfall thresholds but the skill is maintained through the first 3 days of the forecast. Verification of forecast winds at a range of vertical levels against the model's own analysis suggests that there is reasonable skill for the first three days of forecast, both for large-scale features and changes, which is useful for flight planning.

3.2 Medium-range

The Met Office GloSea5 forecasts, from April and May start dates, indicated dry conditions in June 2015. The observed rainfall anomaly for June also indicated a suppressed monsoon, as the west coast and monsoon trough regions showed below normal rainfall. On the medium-range timescale, week-2 forecasts for different weeks of June showed good skill. During the first two weeks (1-7 & 8th -14th June), the west coast and monsoon trough had dry anomalies, which were predicted by the GloSea5 coupled system two weeks in advance. During the week 15th -21st June, it started raining over parts of the west coast and eastern India, but north India remained dry. Similar conditions were forecast in GloSea5 two weeks in advance (figure 9). Then, during 22nd-28th June, the monsoon trough region (northern central India and northern Bay of Bengal) had a good amount of rainfall. GloSea5 also predicted this feature, two weeks in advance.

5. Conclusions

As part of the INCOMPASS project, the FAAM BAe-146 research aircraft travelled to India, from May to July 2016, to record key aspects of the Indian summer monsoon onset. As well as the aircraft campaign, there was an intensive ground based campaign, collecting surface and upper air measurements from radiosondes, flux towers and various other instruments. During planning for the airborne part of the campaign, partners in the UK and India took part in a dry-run forecasting exercise for the 2015 monsoon, to assess the reliability of the forecast products and develop a set of flight plans, with protocols for when they should be used.

UK Met Office Unified Model global operational model and Indian NCMRWF NCUM 5-day forecasts showed good skill in terms of rainfall in regions key to the campaign in north and south India, and in predicting the advance of rainfall over India during the onset, and captured transitions from active monsoon conditions to break and back to active.

We observed a number of key phenomena. Prior to monsoon onset, a western disturbance brought some rainfall to the northwest of the region, and some relief from the unusually high pre-monsoon heatwave conditions over India. Dry intrusions provide an important control on the development of convective clouds and are thought to be important in the progression of the monsoon onset northwest over northern India, against the synoptic flow (Parker et al., 2016). As such, they can be used to help predict the development of convective storms during observational campaigns. Cyclone Ashobaa formed in the Arabian Sea from the monsoon onset vortex, and eventually dissipated as it approached the Oman coast, while Cyclone Komen was the first cyclone to form in the Bay of Bengal in 25 years, and caused significant damage and flooding to parts of Myanmar, Bangladesh and West Bengal. Errors in forecasts of the position of cyclone Ashobaa in the Arabian Sea, from 6th-8th June led to too slow progress of the monsoon onset on the west coast of India, while the path of cyclone Komen was not captured by a number of leading models.

As a result of this dry-run forecasting exercise, a number of flight plans for research flights were developed for the 2016 aircraft campaign in India, based on our observations of the development of the monsoon over India and some of the phenomena that occurred during that time. While the 2016 monsoon is of course not a repeat of 2015, the flight plans developed, after some refinements, will form the flight plans for the actual campaign, and the understanding gained has played a vital role in the lead-up to the main campaign

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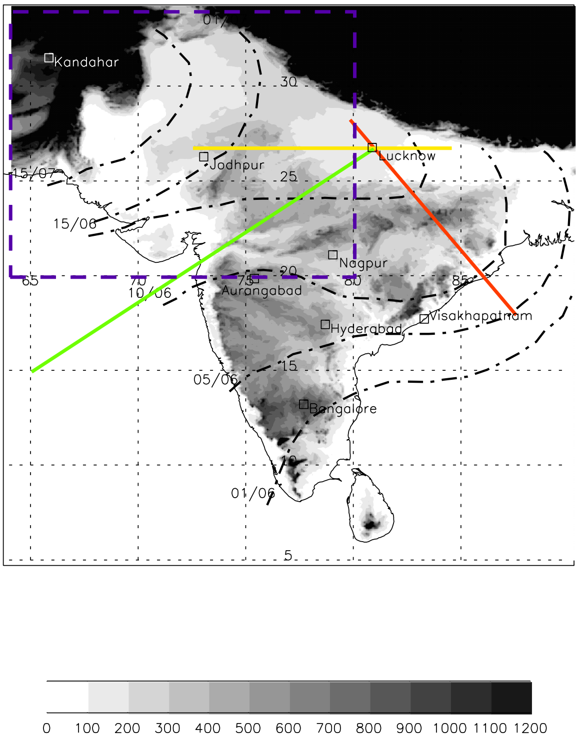


Figure 1: Orography of field campaign area of interest, with proposed flight tracks from north India base in Lucknow, and isochrones (dot-dashed lines) showing the climatological monsoon onset dates The green northeasterly track into the Arabian Sea was designed to sample an Arabian Sea cyclone, like Cyclone Ashobaa, while the yellow and red lines would be primarily to capture the development of the Indian monsoon as the onset occurs over India. The purple dashed line outlines the region shown in figure 3.

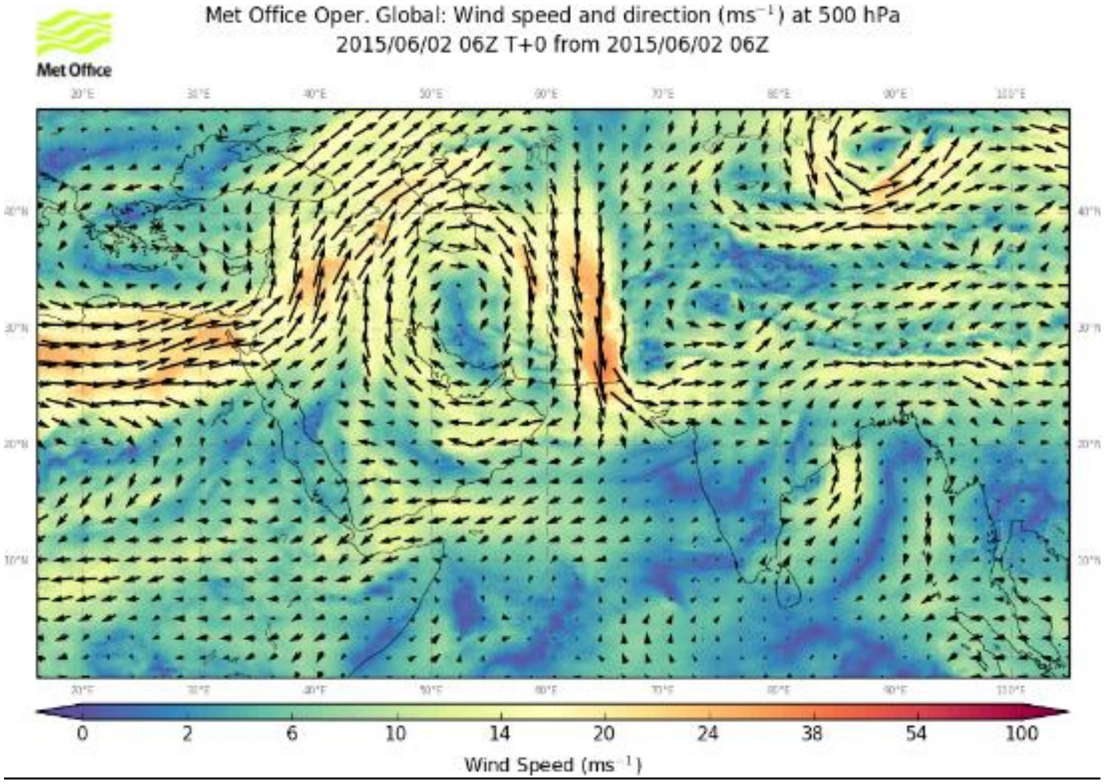


Figure 2: 500 hPa wind speed and direction from MetUM operational global analysis at 06Z 2nd June 2015.

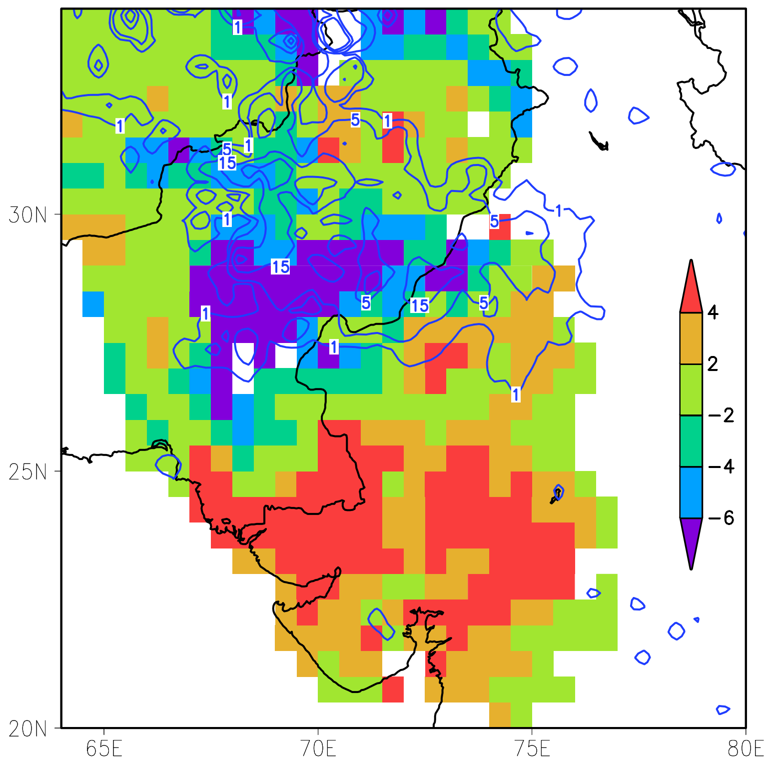


Figure 3: Aqua satellite land surface temperature anomaly at 1330 local time 29th May 2015, compared to the long-term climatology (colours), in northwest of region (see figure). The coastline is in light gray, starting at ~26N on the western boundary. The contours are TRMM 3B42 rainfall accumulated between 06UTC 27th May and 06UTC 29th May.

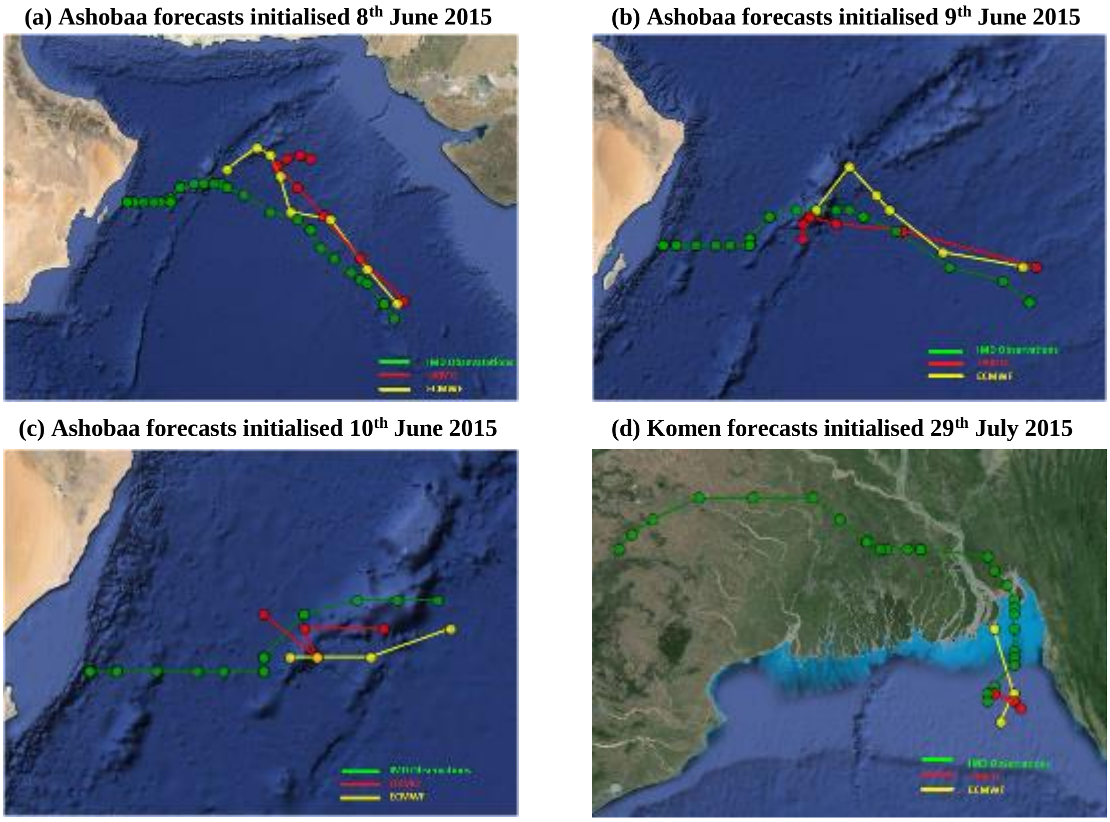


Figure 4: Forecast and observed tracks for cyclones “Ashobaa” and “Komen”, with points every 12 hours from initialisation. Observed tracks from Indian Meteorological Department; forecast tracks (with varying initialisation dates) from UK Met Office (UKMO) and the European Centre for Medium Range Weather Forecasting (ECMWF). Note that verification is only carried out if the cyclone was at tropical storm strength at the verifying time. Hence, the forecast tracks do not extend beyond the time the storms were at storm strength. The CloudSat transect is a satellite overpass profile from 0900UTC on 8th June, which is shown in figure 5.

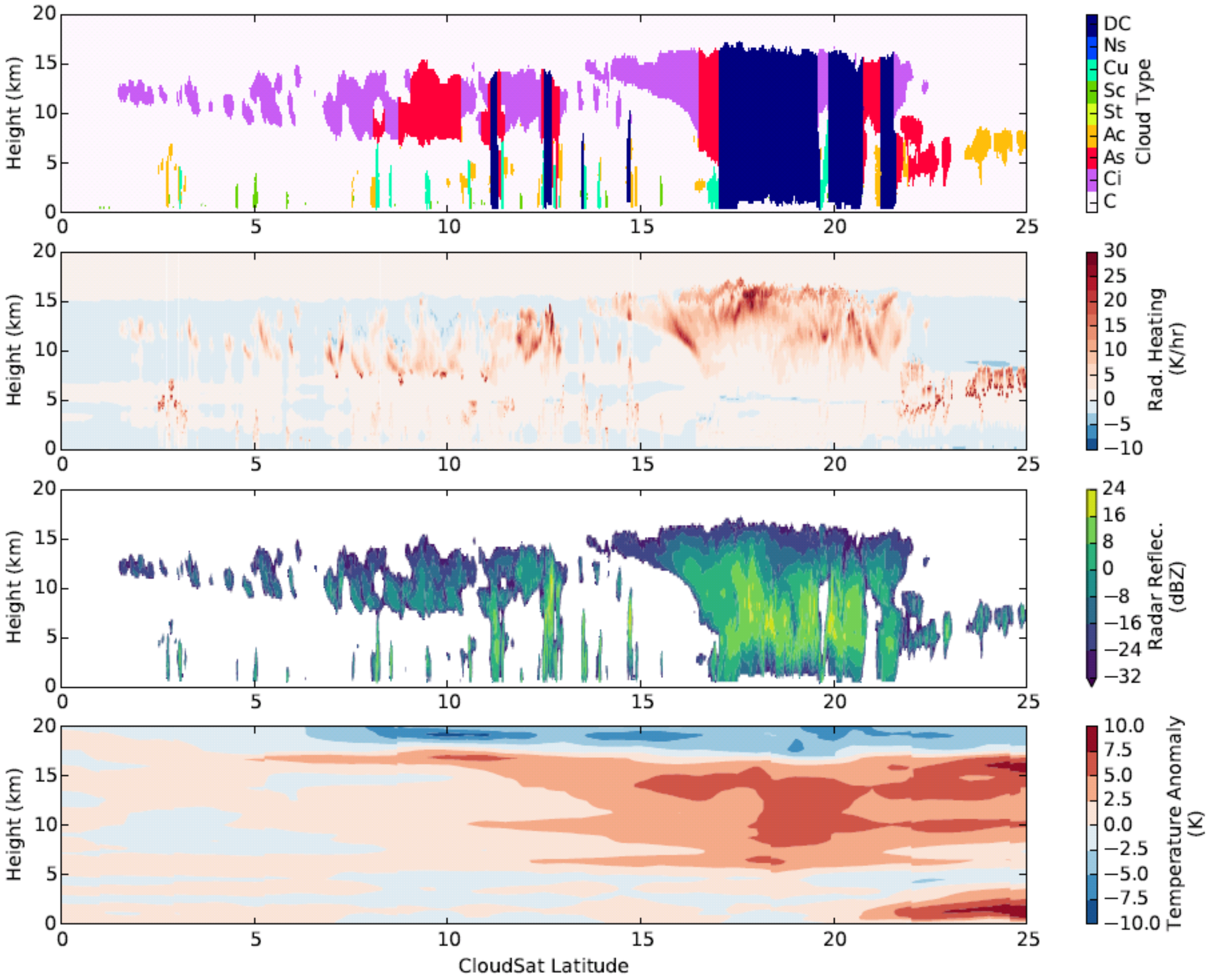
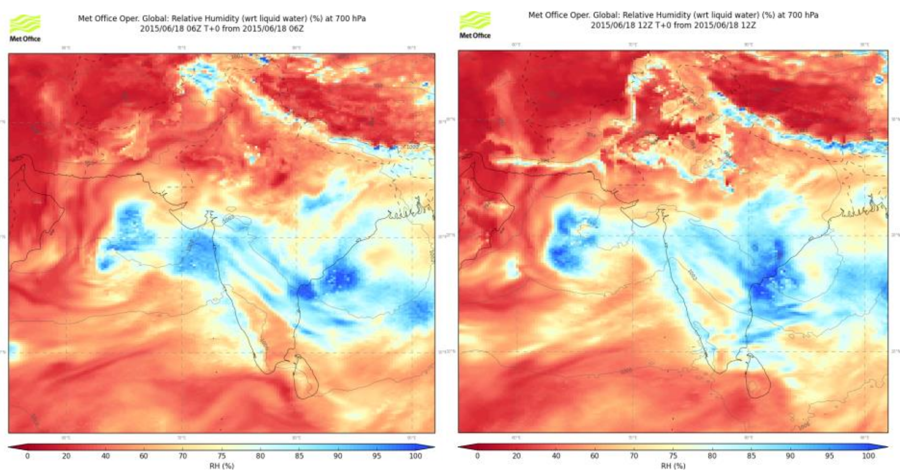


Figure 5: Vertical structure of Ashobaa as seen by CloudSat at 0900UTC on 8th June. (a) cloud type, designated by abbreviations for Clear (C), Cirrus (Ci), Altostratus (As), Altocumulus (Ac), Stratus (St), Stratocumulus (Sc), Cumulus (Cu), Nimbostratus (Ns), Deep Convection (DC); (b) radiative heating (K hr-1); (c) radar reflectivity (dBZ), shown where the data flag indicates the presence of cloud is almost certain; (d) ERA-Interim derived temperature (K), shown as an anomaly to the boreal summer climatology. Theoverpass path is shown in figure 4a.



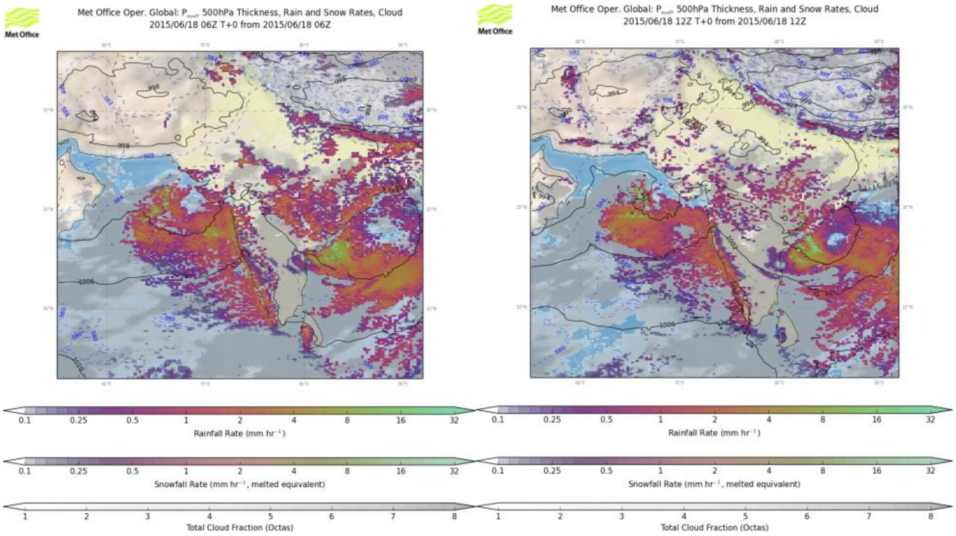


Figure 6: 700 hPa relative humidity (top), and rain and snow rates (colours) and 500 hPa thickness (contours) at 0600 UTC (left) and 1200 UTC 18th June 2015, from the MetUM operational global model output.

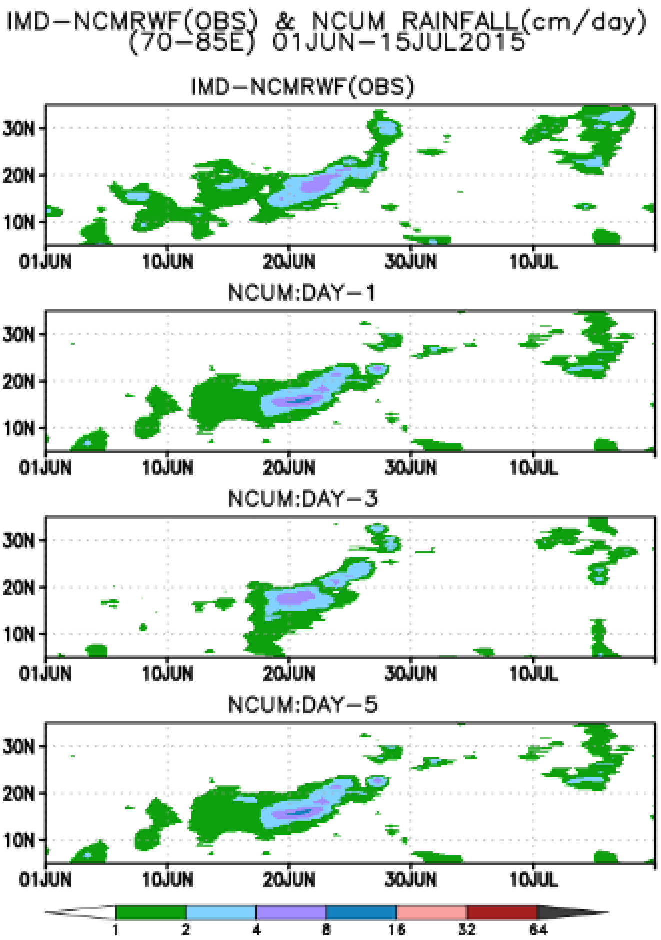


Figure 7: Time-latitude cross section of rainfall averaged between 70-85°E from 1st June to 15th July 2015. Top panel shows combined IMD-NCMRWF observations (Mitra et al., 2013) while subsequent panels show

NCUM forecasts from Day-1, Day-3 and Day-5.

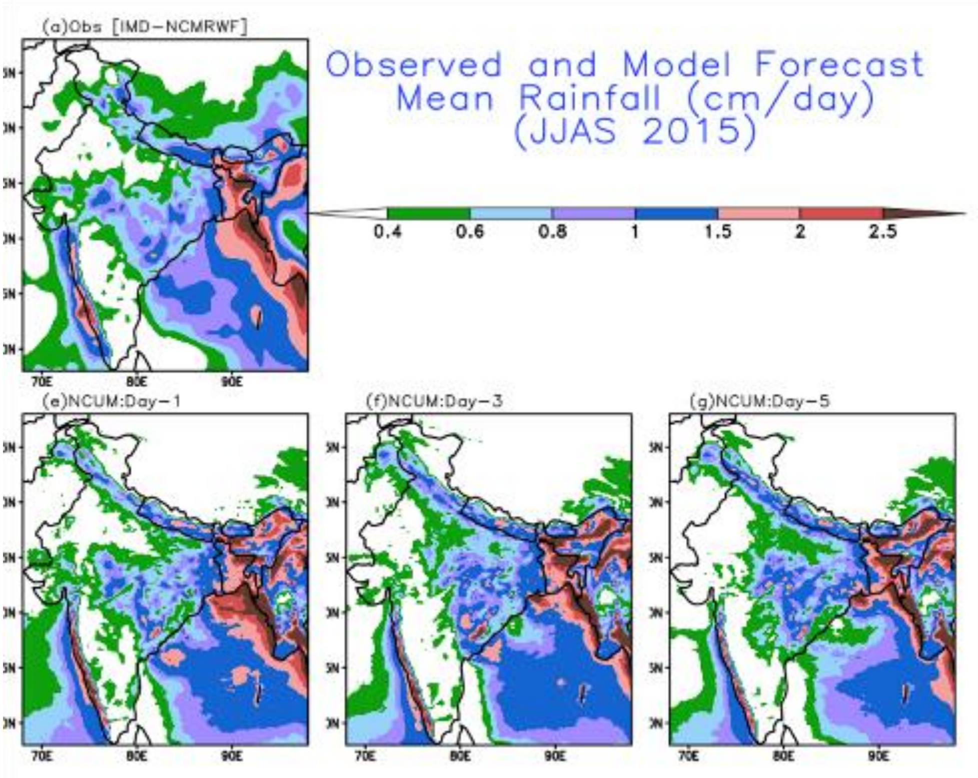
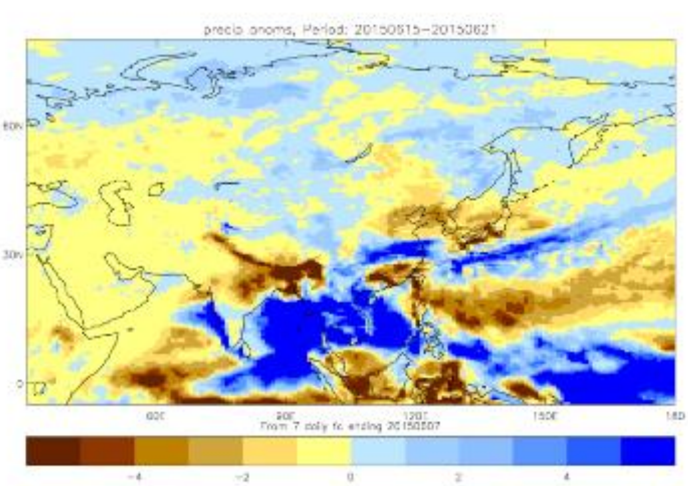


Figure 8 : Comparison of observed and forecast seasonal (June-September) mean rainfall at different forecast lead times between the NCUM forecast model and IMD satellite gauge merged rainfall observations.



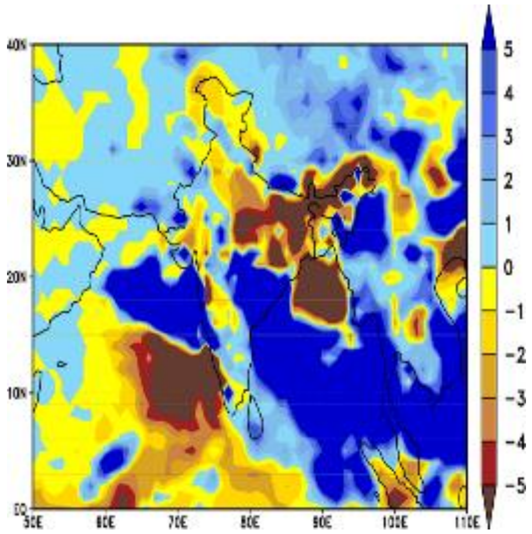


Figure 9: Forecast (top) and observed (bottom) rainfall anomalies (relative to the 15-year climatology; Mitra et al., 2013) from 15th-21st June (mm day-1). Forecast is from GloSea5 with 2-week lead-time, and relative to a 14-year hindcast climatology.